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# PROJECT HINDSIGHT

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## FINAL REPORT

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October 1969

(Data collected prior to July 1967)



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OFFICE OF THE DIRECTOR OF DEFENSE RESEARCH AND ENGINEERING DTI

WASHINGTON, D.C., 20301

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PROJECT HINDSIGHT

Final Report

OCTOBER 1969

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Office of the Director of Defense Research and Engineering (DTI)
Washington, D.C. 20301

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## PREFACE

The Department of Defense, like many other large organizations, pursues a policy of continual introspective examination in order to identify areas in which improvements can be made. Typically, these staff analyses are meaningful and of interest only to selected managers within the Department. On occasion, however, the topic is of such general interest to other branches or agencies of government, or to the public at large, that wider dissemination of the report on the analysis appears warranted. This final report on Project HINDSIGHT is considered as falling into the latter category; in fact, an earlier interim report on HINDSIGHT received wide distribution.

The reader must appreciate that this report covers only a small segment of a much larger area of interest in the dynamics of R&D management. The object of this preface is to emphasize that the Project HINDSIGHT study had certain clearly recognized limitations.

The approach taken in Project HINDSIGHT was essentially retrospective. Twenty recent weapon systems and major military equipments were analyzed by teams of technical specialists to identify applications of science and technology that were not utilized in predecessor military systems designed to meet roughly the same requirements. The evolution of the new technology represented in each system was traced back in time to critical points called "research or exploratory development (RXD) Events." The RXD Event is the basic quantifying unit in the study, and is defined as the occurrence of a novel idea and the subsequent scientific and engineering activity in which the idea is examined or tested. There could be one or two RXD Events, or an extended chain of them, culminating in a device or component found in a particular system.

The teams of specialists identified 710 unique RXD Events, conducted the historical traces, and described and documented the related activities in terms of the differential amount of knowledge that accounts in part for the increased cost-effectiveness of the systems analyzed, compared with their predecessors. These 710 RXD Events represent only a portion of the events that might have been identified by a more exhaustive analysis. To illustrate the gross limits of the study, Project HINDSIGHT concentrated only on the post World War II contributions of science and technology to the selected systems. Each study team was allowed about three months to complete its research on each system.

In treating the sciences, HINDSIGHT distinguished (1) the basic research done to solve a specific assigned problem from (2) the basic research done to expand the frontiers of scientific knowledge; these were categorized as *directed* and *undirected* basic research, respectively. It was found that RXD Events from the directed basic research category emerged in systems development approximately nine years following their conception, while it took 20 or more years for some events from the

undirected category to impact on development. Thus, the HINDSIGHT study did not treat in any depth the contribution from undirected basic research, since many of those events predated the time span of the project.

In short, the HINDSIGHT study was not designed to measure the long term value of basic research. Thus, its conclusions should not be interpreted as presenting any such evaluative judgment or suggesting a plausible basis upon which a judgment of that kind might be made.

Project HINDSIGHT has provided data showing that, broadly speaking, the DoD's requirements are being fulfilled by the results of Defense-supported research and development programs. During the 1946-1963 HINDSIGHT time frame, in which 96 percent of the identified RXD Events occurred, the DoD spent about $10 billion in support of science and technology. Also during this period, industry and other Federal agencies spent about $6 billion in the same areas. It might be expected, then, that about 40 percent of DoD-utilized science and technology would come from these other sources. In fact, Project HINDSIGHT found that 95 percent of DoD-utilized knowledge came from scientific and technological activities supported either directly or indirectly by the Department of Defense. The DoD will therefore continue to ask for the necessary resources to fund and manage broad research and development programs that are responsive to our short- and long-term needs for weapon systems.

Some results of Project HINDSIGHT suggested that the interaction of scientific and technological knowledge is stimulated by, and is most productive for, weapon-system development in a problem-oriented environment. The dynamics and causal relationships between the researcher in the basic sciences and the applied scientist or the technologist are not, of course, completely understood or defined. However, the HINDSIGHT data indicate that 61 percent of the RXD Events identified had a specific systems requirement as an objective and that over 85 percent of the technological events occurred after a problem applications group originally defined the problem to be solved. This finding seems to support the hypothesis that the rate of transfer and utilization of scientific and technical knowledge may well be increased when a specific goal or system problem provides the impetus.

The Department of Defense recognizes clearly that the HINDSIGHT project has *not* studied, in any comprehensive way, the influence of science on the development of technology. There are findings here which demonstrate that the basic research community clearly contributes to systems development—for example, through the fundamental process of educating those who become the inventors and users—but the study did *not* examine the role of basic science. The HINDSIGHT report and other subsequent analyses of the interaction between science and technology have not altered the strong *philosophical* commitment of the DoD to an aggressive, high-quality program of research in the basic sciences. Such a program is critically important to our future national security.

In summary, Project HINDSIGHT made a significant contribution toward a better understanding of the forces and environment that foster the flow of technology into weapon-system development. It does not represent a total or final answer; rather, it is one element in the national effort to enhance the management of research and development resources.

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## ACKNOWLEDGMENTS


The design and conduct of the experiment, the analysis and interpretation of data and the report's preparation were accomplished by the undersigned and are fully his responsibility. Opinions expressed or implied are not necessarily shared by the Department of Defense or its principal officials.

Credit for the accomplishment of this study is gratefully shared with:

*Dr. Chalmers W. Sherwin,* Department of Commerce, formerly Deputy Director of Defense Research and Engineering (Research and Technology), who recognized the potential of a critical analysis of weapon history to provide guidance for improved management of research and who provided executive control over Project HINDSIGHT.

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*Dr. Richard A. Weiss,* Department of the Army
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*Colonel James E. Paschall,* Department of the Air Force

who gave support and guidance and assisted in managing the field teams that collected most of the data.

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who, in addition to their normal duties, diligently undertook the difficult task of tracing people and ideas through 25 years of history.

The many hundreds of respondents who took time to search old files and their memories for the desired information.

Appreciation is expressed to the [illegible], particularly [illegible], who directed the technical editing of field reports, the extraction of requisite information, and the data processing services; to the staff of Arthur D. Little, Inc.; and to [illegible], whose efforts during the pilot studies provided some of the raw data and considerable guidance in the design of the experiment, Project HINDSIGHT.

Raymond S. Isenson
Colonel, U.S. Army
Director, Project HINDSIGHT

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## EXECUTIVE SUMMARY

Project HINDSIGHT was established by the Director of Defense Research and Engineering in his memorandum of 6 July 1965 to the Assistant Secretaries (Research and Development) of the Military Departments. (See Appendix A.)

### Objectives and Strategy

The defined objectives of Project HINDSIGHT were:

(a) To identify those management factors that are important in assuring that research and technology programs will be productive and that program results will be utilized; and

(b) To measure the overall increase in cost-effectiveness in the current generation of weapon systems compared to that of their predecessors (when such can be identified) that is assignable to any part of the DoD's investment in research in science and technology.

The strategy adopted to achieve these objectives involved:

(1) Determining the extent to which new weapon systems are actually dependent upon the results of recent advances in science or technology for their attained increase in system effectiveness, decrease in cost, or increase in cost-effectiveness as compared to a predecessor system.

(2) Determining the proportion of any new technology, required for attaining system characteristics, that was the result of DoD-financed research in science or technology.

(3) Determining significant management and other environmental factors, as seen by the research scientist or engineer, that appear to be commensurate with high utilization of research results.

(4) If the findings of the first strategy indicate a significant reliance on new science or technology, devising a value-cost index (or set of indices) which offers a quantitative measure of the return on investment in research, in terms of the enhanced cost-effectiveness of the weapon systems made possible by the purchased knowledge.

The study efforts were organized to offer, in a comparatively brief period of time, the class of information that could be of primary use to senior management levels of the DoD and the military services. These objectives have been achieved. This report describes the findings and, where appropriate, suggests their implications. More detailed information which—although it might have some policy implications—is of

greater interest to the lower management echelons within the scientific and technological communities will be developed later.

The study personnel consisted of the following:

Ad hoc teams of military and civilian in-house (DoD) personnel;

Consultive and participating contract support by behavioral and management scientists from Northwestern University and the Sloan School, Massachusetts Institute of Technology;

Contract support by econometrics scientists from the Institute for Defense Analyses (IDA) and the Rand Corporation; and

Voluntary participating support from five industrial-management scientists.

The in-house teams were concerned with establishing the amount of new science or technology embodied in modern weapon systems, ascertaining the financial support for this science or technology, and defining gross management patterns. The university and industrial-management scientists are concerned with the more subtle aspects of research management, including idea flow, information sources, training, individual effectiveness and motivation. IDA and RAND are attempting to devise credible and useful value-cost indices for research.

Methodology

Each in-house team focused on a single weapon system. The subsystems, components, materials and enabling system concepts were examined in detail for evidence of the application of knowledge resulting from recent research in science or technology. Subsequent to the recognition of this evidence, each team undertook an investigation to ascertain the source of the new knowledge and the circumstances under which the knowledge was generated and passed to the eventual user.

The basic element for quantification within Project HINDSIGHT is the Research or Exploratory Development (RXD) Event. The RXD Event defines a scientific or engineering activity during a relatively brief period of time that includes the conception of an idea and the initial demonstration of its feasibility. There may be one or two RXD Events, or an extended chain of them, culminating in a device or component found in the studied weapon system. The final fabrication of this component or device may or may not involve an Event, depending upon the state of the technological art at the time of fabrication.

Many observations derived from the analysis of Project HINDSIGHT data confirm widely held assumptions of successful research managers, and in these cases the primary contribution of the Project is to make available quantifiable support for what previously had been informed opinion. There were, however, some significant findings wherein the

data contradict some generally held beliefs. The following paragraphs contain a summary of the findings, based upon analysis of the currently available data, and some interpretation of those findings.

It is emphasized that this study identified only those incremental contributions to existing bodies of scientific and technological knowledge that were utilized in the analyzed military equipments. The strong dependence of these contribution upon the total base of science and technology must be recognized. The reader is cautioned that any conclusions regarding the value of the total knowledge base cannot be validly drawn from the findings presented here.

HINDSIGHT Findings

*(1) The identification of specific events in science or technology research, the results of which were utilized in, and were critical to, new weapon systems, was found to be fairly simple.*

For most of the systems studied, on the order of 100 to 150 post-1945 contributions from the scientific and technological communities were uncovered. Practical limitations in time and resources, however, permitted only a smaller number to be examined in detail. In no case did the study team feel that it had exhausted the possibilities for identifying additional contributions. Studies of the individual systems were terminated when the study team and the Project Director were quite certain that a representative sample of the contributing Events had been investigated or a 3-month study period had elapsed, whichever came later. Estimates of sample size, made at the completion of the system study, varied from 20 percent for the C-141 cargo aircraft to 75 percent for the LANCE missile system and over 95 percent for the Mark 56 and 57 Naval mines.

*(2) The number of Events that were easily identified varied proportionately with the relative increase in effectiveness between the studied system and its predecessor.*

For example, the studies quantitatively demonstrate that more new technology was required to progress from the HONEST JOHN rocket to the LANCE missile system than from MINUTEMAN I to MINUTEMAN II.

*(3) No category of performing agency was found to be significantly more efficient in the production of utilized research results than other categories.*

The distribution of identified RXD Events that came from universities, industry, or the in-house laboratories of the Military Departments agrees, to within a very few percentage points, with the allocation of applied research funds to these categories.

*(4) The study's findings demonstrate that the results of research in science were most frequently exploited when the investigator was responsive to recognized needs of the engineering community.*

Although the profitable work frequently was classifiable as applied research, in that the scientist was attempting to resolve a very specific problem, it does not appear that specific application per se is a sufficient criterion for predicting usage. Perhaps the most important factors in establishing a high probability of utilization are the degree of awareness (a) on the part of the scientist concerning who in the engineering community needs the knowledge and (b) on the part of the interested engineers as to which specific scientist is working on the problem. Accordingly, research managers must be sensitive to the need for communication between the scientific and engineering communities.

Four sets of scientific Events that assume great importance because of the number of systems that rely upon them are readily distinguishable. They include work that led to information and filter theory, inertial guidance components, rocket engines and propellants, and transistor technology with its associated miniature passive electronic elements. In each case the preponderance of the research effort was independent of any specific weapon-system development, but was found to have been guided by individuals who were acutely aware of the detailed problems confronting design engineers and of the limits imposed on achievable system performance by available pertinent technology.

*(5) A significant number of important scientific contributions came from sources other than contemporarily recognized experts.*

Investigation of a sampling of these Events disclosed a fairly common pattern. The performers of the utilized scientific effort and their peers were mutually aware of the exploration each was undertaking, but there was marked disagreement regarding the merit of the approach that eventually found use. In each case the successful performer broke from the peer group, moved away, and found new funding. More than anything else, these examples point out the necessity for ensuring competition within bureaucracy and the necessity for maintaining a multiplicity of funding sources for every scientific discipline and area of technology.

When high payoff from scientific research at universities was identified, the scientific research was coupled closely to research in technology and some limited development. Typical examples are the inertial guidance theory and component work at the Instrumentation Laboratory, MIT, and the propellant research at the Jet Propulsion Laboratory, California Institute of Technology.

Within this report, undirected basic research in science, as defined in Table III (page 14), refers to tasks not clearly identifiable as part of a larger program that was coordinated by a mission-oriented agency. In general, they are those individual, comparatively small efforts undertaken by one or two investigators in the universities, in some not-for-profit corporations and, to a much smaller extent, in other

industry. They are characterized by the fact that they were motivated at the researcher's level by scientific curiosity and scholarly inquiry, and were supported by the DoD upon recognition of the relevance and significance of the researcher's proposal.

An important payoff from scientific research at universities has been through the schooled scientists and engineers who later performed the applied research. Of the 1,795 individuals identified as having contributed to an RXD Event, detailed information is currently available on 511, of whom 92 percent hold academic degrees in science or engineering. The observation that the practicing engineer tends to depend largely upon unified theory (e.g., Kepler's, Newton's and Boyles' laws and Maxwell's equations) suggests that a major payoff of undirected basic research is through knowledge acquired during undergraduate education.

During FY 1965, based on a percentage breakout of research and development funds, approximately 26 percent of the nation's scientific and engineering talent was employed directly or indirectly by the Department of Defense. This figure has remained fairly constant over the past several years. As a major user of these resources, the DoD should have a selfish interest in ensuring the continued supply of talent by guiding potential ability into scientific disciplines or technical areas of marked military relevance. The selective use of research grants and contracts is one way of affording such guidance.

Complementing this knowledge accrued through formal education is the engineer's later recourse to codified or tabulated information, such as engineering handbooks and technical references. The second payoff of basic scientific research is identified as the organization of research results into a format readily available for general use. In this way, new concepts of everything from materials characteristics to design techniques have been widely disseminated. Management criteria intended to enhance the usefulness of research results should include recognition of the importance of unifying or codifying information and the requirement that the objectives of supported research be so oriented. Periodic surveys should be made, and research advances in particular subject areas should be consolidated and published in a format designed for use by engineers.

*(6) The greatest payoff in terms of ideas leading to enhanced weapon systems has resulted from research in technology—and then, where the research scientist or engineer was intimately aware of problems of the applications engineer.*

The transfer of science to technology and technology to application has been found to rely heavily on personal contact between individuals (see Table VI, page 47). The communication link is of critical importance, both for advising the scientific community about real problem areas and for disseminating scientific or technological knowledge to the eventual user, the applications engineer.

*[illegible]*

The real difference in performance between a weapon system and its predecessor is usually not the consequence of one, two or three scientific advances or technological capabilities but is the synergistic effect of 100, 200 or 300 advances, each of which alone is relatively insignificant. These hundreds of diverse advances must then be fitted and adjusted for a unified operational weapon system. The characteristics of each advance must be carefully "interfaced" with those of other advances. This is substantiated by Project HINDSIGHT data, which generally show that systems applications, rather than new science, inspire science and technology for advanced systems.

*(8) A considerable amount of new technology is dependent upon prior specification of detailed requirements.*

Analysis of the time relationship of an RXD Event's occurrence to its utilization in the studied system reveals two characteristic patterns. Where the weapon-system development progressed directly from a technological base (exploratory development) to engineering development, there is a marked peaking of Events about the time development is initiated, with about 41 percent for LANCE and 60 percent for MINUTEMAN II occurring after development had started. This situation appears to be incompatible with current procurement policies that stress fixed-price development contracts (with or without incentive fee). Where the weapon system progressed from a technological base through an advanced-development phase and then into engineering development, a much more uniform distribution, devoid of significant peaks, is noted; examples are the Mark 56 and 57 Naval mines.

Project HINDSIGHT did not investigate system-management aspects of the weapon systems studied. It is understood, however, that in at least three cases—the BULLPUP air-to-surface missile, the C-141 cargo aircraft and the LANCE missile system—development was undertaken after assurance was given that the requisite scientific and technological knowledge was in hand. The Event-distribution charts adequately demonstrate that these assurances were not valid. A major reason for the lack of validity becomes apparent in a study of the detailed Event descript ons. At the time an advanced weapon system is proposed, the design engineer forms his judgments on the basis of experience or the extrapolation of that experience—the more advanced the proposed system, the greater the dependence upon extrapolation. A requirement for research in technology arises when the extrapolation proves to have been overly optimistic.

In view of the potential economic advantages of fixed-price system-development contracts, the matter becomes one of determining how, in the light of Project HINDSIGHT findings, it is possible to ensure that such a contractual situation can be meaningfully established without

restricting technological growth. Two possibilities (findings 9 and 10), either or both, are suggested as a solution to the problem:

*(9) [illegible]*

The Mark 56 and 57 Naval mines, developed in an environment that currently would be considered advanced development (R&D category 6.3), demonstrate what can be done. The apparent rate at which technology was introduced shows the orderly progress that is possible throughout development in the absence of a production commitment or an overly ambitious delivery schedule. The investigation disclosed that, during the early development years, the work was accomplished at an essentially constant level of effort. Fixed sums of money were made available for investigations into problem areas that were disclosed as the system's design took shape. Production did not start until a prototype demonstrating that the problems had been reduced was essentially complete. These examples suggest that the greater use of prototype-system development in the advanced-development category, to provide focus and spur to research in science and technology, can be a successful prelude to fixed-price production contracting and still ensure a significant increase in operational performance.

*(10) Visibility of research expenditures can be retained by means of budgeting techniques.*

Alternatively, fixed-price development contracting might be made feasible by assigning to the Government project manager a degree of control over a portion of the Military Department's technology money (R&D categories 6.1, 6.2 and 6.3) in addition to the engineering-development (6.4) money committed to the contractor. This would allow the project manager to influence the development of the necessary technology for his system, ensure that the technology money was in fact directed into areas of established military importance, and by keeping the fund in the 6.1, 6.2 or 6.3 categories give visibility to expenditures. It is clear that the use of this technology money must remain responsive to the control of the Government project manager to be parceled out as needed. Obviously, great care must be taken to ensure that these funds don't become a "bail-out" resource to cover nontechnical management deficiencies. Examples of the successful application of this approach were found in the development of the Mark 46 torpedo and the AN/SPS-48 radar.

*(11) The DoD has required a considerable amount of new technology and has had to fund most of it.*

The relative ease with which RXD Events contributing to the capabilities of new weapon systems were identified, the number and diversity of those Events, and the recognition that the same level of the utilized science or technology almost never existed at the time of engineering

development of an operationally similar predecessor system combine to demonstrate irrevocably that a considerable amount of truly new technology was required for an advanced weapon system.

It is estimated the Military Departments spent about $10 billion during 1945-1963 when most of the identified Events occurred (see Appendix F). For the same years, another estimate places expenditures for research in science and technology by industry and other non-Defense sectors of the economy at approximately $7 billion. The finding that the acquisition of 85 percent of the utilized new scientific and technological information was financed by the Military Departments becomes significant in view of the relative size of the two amounts expended.

We may conclude from these two observations that a great deal of new knowledge was required for an advanced weapon system and the Department of Defense could not rely on other sectors of the economy to generate it. This conclusion is strengthened by the finding that, of the remaining 17 percent not directly funded by the DoD, 9 percent was paid for by defense-oriented industries and was thus indirectly funded by income from previous Defense contracts.

*(12) Transfer of technological information is at a reasonably high level within the defense-oriented community.*

Approximately 300 separate organizations or corporations have been identified as having contributed to the fund of new knowledge. About 20 of them had significant responsibility as prime contractors in the development of one or two of the studied systems. Despite the great number of participants, over 80 percent of the RXD Events (but an estimated 20 percent within the set of systems studied) are known to have found application in more than one weapon system. At the very least, therefore, it can be claimed there are strong indications that information transfer within the defense engineering community is at a usefully high level.

The Project HINDSIGHT study did not attempt explicitly to identify alternative technologies used in the several systems where one of the alternatives theoretically might have satisfied all users. The number of cases involving such a situation was so small as to appear statistically insignificant.

*(13) The performance of the in-house DoD laboratories appears to be consistent with the numerical strength of their professional personnel.*

After the sources of the utilized new science and technology were identified, it was possible to examine time-dependent trends in terms of the relative productivity of the various sources. As far as new science is concerned, the available data are not statistically significant. A marked trend, however, is observable with respect to technological activity. Early in the 1945-1958 period, about 51 percent of the new technology was coming from the in-house laboratories of the Military Departments, with 42 percent from industry and 7 percent from the universities.

By 1959 the balance was reversed, so that 36 percent was coming from the Defense laboratories, 58 percent from industry, and 6 percent from the universities (primarily university-operated centers such as the Research Laboratory for Electronics or the Instrumentation Laboratory at MIT).

During this whole time, the scientific and engineering strength of the non-DoD community essentially quadrupled, while the strength of the in-house Defense laboratories less than doubled. Thus, the change in relative output appears to reflect only the relative increase in strength.

## Findings Pertinent to Strategies Used

In terms of the four strategies employed to attain the primary objectives of Project HINDSIGHT, the relevant findings are summarized here.

> Strategy 1: Determine the extent to which new weapon systems are actually dependent upon the results of *recent advances* in science or technology for their attained increase in system effectiveness, decrease in cost, or increase in cost-effectiveness as compared to a predecessor system.

Findings: Markedly improved weapon systems result from skillfully combining a considerable number of scientific and technological advances.

There is a high positive correlation between the relative sophistication of the predecessor and successor systems—or the relative increase in their effectiveness—and the amount of new science or new technology utilized in the successor.

> Strategy 2: Determine the proportion of any new technology, required for attaining system characteristics, that was the result of DoD-financed research in science or technology.

Finding: More than 85 percent of the new science or technology utilized in weapon systems was the result of DoD-financed programs.

> Strategy 3: Determine significant management and other environmental factors, as seen by the research scientist or engineer, that appear to be commensurate with high utilization of research results.

Findings: The utilization factor appears insensitive to classical differences in organizational structure or profit motivation appearing between U.S. industry, in-house DoD laboratories, and university-associated science and technology centers. It may, however, be sensitive to differences between these types of organization and the classic organizational structure of universities.

Most utilized new scientific information came from organized research programs undertaken in response to recognized Defense problems.

The most useful role of science has generally been that of providing phenomenological explanations to the engineer.

The engineer uses unified scientific theory and codified scientific information.

The program of research in technology oriented toward specific types of equipment has been a particularly successful approach to generating utilized knowledge.

Achievement of a high combined inventiveness, or ingenuity, and utilization rate are dependent upon the time and space coexistence of four primary factors—the recognition of need, a source of ideas in the form of an educated talent pool, capital resources, and an adequate communication path to potential users.

> Stra'gy 4: If the findings of the first strategy indi te a significant reliance on new science or technology, devise a value-cost index (or set of indices) which offers a quantitative measure of the return on investment in research, in terms of the enhanced cost-effectiveness of the weapon systems made possible by the purchased knowledge. [This objective has not yet been satisfied. Relevant findings serve primarily to define the problem further.]

Findings: A number of factors identified through the studies made thus far tend to refute the possibility that any simple or linear relationship exists between cost of research and value received. They include the following:

(a) There is a high probability that any given scientific or technological advance, if used in one system, will be used in many other systems. Thus, any cost-value index must either apportion the research cost among all utilizing systems or attribute a portion of the total value added by each utilizing system to the identified RXD Event.

(b) Improved weapon systems or end-item equipments tend to be a synergistic rather than cumulative consequence of the several embodied scientific and technological advances. Thus the task of apportioning value added becomes complex.

(c) The relative amount of new scientific or technological knowledge required to achieve greater effectiveness, lower cost or improved cost-effectiveness of a new system, as compared to that of a predecessor system, increases with the latter's technical complexity.

Thus, any crude approximation in measuring value added as a consequence of research expenditures will tend to be delusory in that return on investment will always appear greater when an improvement is made in a simple system.

* * *

As a final note, two matters must be emphasized.

First, the scope of this study and its resultant findings are concerned only with the acquisition of knowledge essential to the technological development of a weapon system. Questions concerning the use or value of the results of research in the behavioral, life environmental or social sciences were not addressed.

Second, none of the findings described above should be interpreted as a disavowal of the value of very fundamental research in science. It is hardly likely that the transistor could have been invented by people who sought a smaller, more rugged electronic signal amplifier but were unversed in wave mechanics or the theory of electrons in solids; that a search for new power sources would have led to the nucleus of the atom in the absence of the work of Curie, Fermi and others; or that radio or telephone communications could have been invented without the research efforts of Hertz, Maxwell, Marconi and their fellows.

The findings suggest only that defense research is most likely to culminate in utilization when deliberate attempts are made to relate the research results to the problems of the military services.

# I. INTRODUCTION

Project HINDSIGHT is a historical survey of the process by which modern weapon systems and current operational procedures acquire their scientific and technological bases. The studies are focused on:

(1) the people who can be identified as having played significant roles in the acquisition of this knowledge, the management environments in which they worked, and the behavioral patterns they exhibit;

(2) analysis of the utilized technology, time distributions between a discovery or invention and its application, uniqueness in terms of areas of practical application, sources, interaction between the recognition of requirements and the generation of new knowledge; and

(3) econometric investigations of research in science and technology, estimates of the value-cost ratio of this research, and development of new analytical tools to provide management measures of the effectiveness of research.

The time frame of primary interest in the study is the period from 1945 to the present.

The history of military support of research in science and technology in the United States dates back almost to the time of the organization of the military services. Although the resources available for commitment to these activities undoubtedly fluctuated with national prosperity, congressional or executive moods and specific exigencies of the services, a number of factors combined to minimize inherent difficulties in the management of whatever research programs existed prior to 1940:

First, until the latter part of the 1930s, the lack of military interest in recognized scientific opportunities limited the number and scope of potential investigations.

Second, the research potential of the nation resided primarily in its universities, and communication channels between the academic and military communities were practically nonexistent.

Third, the total funds available, either in terms relative to current annual expenditures for research or in terms relative to contemporary defense budgets, were so small that their management constituted no problem.

Fourth, the contemporary practice of supporting research out of the development program for which the knowledge was desired afforded a level of coupling, or visibility, that minimized any requirement for separate justification.

Starting about 1940, several factors combined to cause extensive changes in the defense research environment. Fundamental discoveries in the sciences, particularly in quantum physics, electronics and chemistry, had significantly increased opportunities for defense oriented research. The high level of support given to research during World War II not only resulted in the proliferation of scientists within and outside the universities, but in addition created communication channels between the scientists and the military.

The potential application of new knowledge across a multiplicity of advanced weapon systems and the increasing costs of research combined to introduce a concept of research supported separately from specific weapons or weapon systems. An unstable post World War II political environment encouraged an iterative process of acquiring and using new knowledge leading to advanced weapon systems, which in turn established requirements for more knowledge to enable more advanced defensive or counteroffensive weapons. This provided the justification for a steadily increasing level of expenditure for research.

Between 1945 and 1963 an estimated $10 billion was spent by the Military Departments for research in science and technology. In FY 1966 alone, $1.4 billion was programed for this endeavor. In both relative and absolute terms, the rate of expenditure had grown to the point at which searching questions by "Management" were inevitable and essential. Project HINDSIGHT was established in order to determine analytically—

- the importance of research in science and technology to the Department of Defense;

- the uniqueness of Defense requirements for research, if any;

- management factors that significantly influence the productivity of research; and

- answers to many of the other questions that have been raised by conscientious administrators.

Specific questions have been as varied as the background and interests of the individuals posing them. However, most of the questions—or, more precisely, challenges to the continued support of research—may be fitted into one or more classes. Some of the primary orientations are suggested below. Each is presented in the form of a hypothesis to afford guidance in terms of pertinence of information.

- The Department of Defense's requirements for information in science and technology can be satisfied to such an extent by research supported by the National Aeronautics and Space Administration and the National Science Foundation that significant reductions can be made in the applicable portions of the Defense budget.

• The currently high-level support of basic work is producing scientific and technical information at such a rate that it cannot be effectively digested, interpreted, disseminated, or put to practical use.

• Department of Defense management of research in science and technology, in order to be fully effective, must make comparative cost-effectiveness analyses for each separately identifiable research effort.

• Significant portions of the Defense research program may be operating at or near a point of marginal returns.

• The support of scientific research in the universities, by the Department of Defense and at current funding levels, significantly affects the availability of the best faculty talent to teach students.

The requirement for judgment criteria, implicit in each of these hypotheses, suggests that an analysis of the historical use of research-generated knowledge cannot alone provide fully satisfactory proof or refutation. Project HINDSIGHT recognizes this situation and adopts some augmenting hypotheses, the test of which will offer further evidence for or against the previous set, and also will provide some guidance to management where the findings are less than satisfactory. The supplemental set concerns itself with management factors affecting the use of research results. The concept implicit in this approach is based on the argument that, if the management factors encouraging the use of research can be identified, current management practices can be comparatively analyzed and modified, where and if necessary. The general themes of the propositions tested in the supplemental hypotheses include the following:

Criteria—The strategies used by individuals and groups in the selection of research tasks whose results were utilized.

Control—The nature of the control environment within which successful groups work; the degree of freedom of choice and action by the various levels *vis-à-vis* their superiors and the larger environment; the degree and nature of authority over fiscal and technical matters at the various levels.

Skills—The way in which new scientific and technical skills are developed; the role the skills play in accomplishing utilized research; factors influencing the cost and time of moving into a new field: the use and effectiveness of retraining and continued graduate studies.

Interface—Relations between the successfully performing research group and organizations involved in other phases of the RDT&E (research, development, test and evaluation) cycle; the significance of communications lag and distortion; the value of liaison individuals.

Idea flow—Conditions in the immediate (group) and larger (organization) environments that influence the kind, number, source, communication and disposition of ideas for new investigations.

Use of information—the kinds of search strategy used by successful individuals and groups in obtaining technical information; the influence of time and financial and communication constraints on search strategy; the influence of search strategy on the productivity of the individuals and groups.

The study methodology employed in the various tasks making up Project HINDSIGHT is described in detail in section 2, "Objectives, Strategy and Methodology." Conceptually, the procedures are summarized in the following paragraphs.

## Task I: RXD Events

Research in science and technology is a continuing activity of the Department of Defense. If this activity is of value, it would be logical to expect that a generation of weapon systems would evidence the consequences of this research—that it would be based not only on the scientific and technical foundation of preceding generations, but on new knowledge as well. This assumption provides the basis for the historical studies comprising Task I of Project HINDSIGHT.

The Task I studies constitute the sole basis of this report. For this first task, 20 modern weapon systems or military end-item equipments have been examined by teams of experienced scientists and engineers for evidence of science or technology that was not available or was not utilized in predecessor systems. Having recognized the application of this new knowledge, the team undertook a deliberate historical trace of the component, technique or idea. The objective of the trace was to identify the people, the place and the time associated with the generation of the knowledge and with the contribution of significant additions by which the technology reached the level manifested in the studied weapon system.

The primary reason for initiating the studies through the investigation of specific weapon systems is to forestall any doubt concerning the value of the scientific or technological contribution. The focus is on utilized results of investment in research. Project HINDSIGHT is not concerned with management of weapon-system development except when lessons may be drawn from the role of project managers in fostering new scientific or technological knowledge.

The nature and depth of information sought by the Task I study teams are demonstrated in Appendix C, the form used for RXD Event descriptions. At the completion of Task I, 710 RXD Events had been identified, historical traces had been made, the related activities had been described in terms of the differential amount of knowledge that accounts in part for the increased cost-effectiveness of current weapon systems over that of their predecessors. It is estimated that this number represents between one-third and one-half of the RXD Events that might have been identified by a more exhaustive analysis.

### Task II: Behavioral Studies*

Task II studies are focused on the behavioral characteristics of individuals who contributed the utilized knowledge. Management analysts are performing detailed studies of a sampling of organizations and individuals identified in Task I. Areas of investigation include—but are not limited to—idea transfer, skill development, motivation, utilized information sources, and the role of the technical liaison man. As each study is completed, the results will be reported, and the series of topic-oriented essays will be consolidated and published by the Office of the Director of Defense Research and Engineering, probably not until late in 1967. It is anticipated that the behavioral studies will be continued.

### Task III: Econometric Studies*

Task III addresses the problem of defining and implementing a technique (or techniques) for the quantitative analysis of the value of investment in scientific and technological research—its value, that is, in terms of enhanced cost-effectiveness for the resultant weapon systems. A limited effort to achieve a quantitative value differential—again, in terms of predecessor weapon systems—has been undertaken by each of the Task I study teams. To the extent permitted by security restrictions, their findings are reported here. Although a more rigorous approach is being sought by the Institute for Defense Analyses, a useful solution to this very complex problem has not yet been found. Efforts are continuing, and success will be reported if and when experienced.

* * *

The remainder of this report addresses the hypotheses stated on pages 2 and 3 to the extent permitted by the data collected through the studies and investigation conducted under Task I.

Because a number of research procedures were invented for this study or were adapted with marked changes from procedures commonly used in behavioral and other social science research efforts, attention is given in section 2 to methodological details of Project HINDSIGHT. This study, descriptive rather than normative in character, concentrates on a very special class of activities—research efforts whose results are known unequivocally to have been utilized. By focusing on this special class, Project HINDSIGHT accepts the risk of some potentially significant errors of omission. The most apparent of these are discussed and their possible consequences evaluated in section 8, "Methodological Validity."

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*Note: Tasks II and III were discontinued in favor of other related DoD studies.

In general, this report presents observations or conclusions drawn from a first analysis of the collected data, with an interpretation of those observations in terms of their significance to managers of research in science and technology. In a very real sense, this is a partial report. Attention given to the life, behavioral, natural and mathematical sciences is not adequate to warrant an extension of the recommendations to include management of those disciplines. Until further studies are completed, no conclusion can be reached on whether or not implications relating to management in the physical sciences are applicable across other disciplines.

HINDSIGHT is a study of a dynamic sociological situation. It cannot be assumed that observations and findings pertaining to any given time will remain valid over extended periods. Therefore, the necessity for a continuing study or a series of repeated studies is suggested. For this reason and because of the dynamic situation, this report must be considered to be of an interim nature.

## 2. OBJECTIVES, STRATEGY AND METHODOLOGY

### 2.1 Objectives

The primary objectives of Project HINDSIGHT, established by the Director of Defense Research and Engineering (DDR&E) in July 1965 (see Appendix A), were as follows:

> (a) to identify and firmly establish management factors for research and technology programs which have been associated with the utilization of results produced by these programs; (b) to measure the overall increase in cost-effectiveness in the current generation of weapons systems compared to their predecessors (when such can be identified) which is assignable to any part of the total DoD investment in research and technology.

The DDR&E's memorandum concluded several preliminary investigative studies undertaken by the Deputy Director of Defense Research and Engineering (Research and Technology) and accomplished during the previous year, partly under contract with private industry[1] and partly in-house[2]. The pilot studies had demonstrated that at least the first objective was reasonably achievable and had provided insight with regard to more promising procedures.

### 2.2 Strategy and Methodology

The fourfold strategy adopted for satisfying the objectives was relatively simple in concept and may be summarized as follows:

(1) Determine the extent to which new weapon systems are actually dependent upon the results of recent advances in science or technology for their attained increase in system effectiveness, decrease in cost, or increase in cost-effectiveness as compared to a predecessor system.

(2) Determine the proportion of any new technology, required for attaining system characteristics, that was the result of DoD-financed research in science or technology.

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[1]*Management Factors Affecting Research and Exploratory Development*, Arthur D. Little, Inc. (Springfield, Virginia: Clearinghouse for Federal Scientific and Technical Information, AD 618-321, April 1965).

[2]*A Trial Study of the Research and Exploratory-Development Origins of a Weapon System—BULLPUP* (Washington, D.C.: Office of the Director of Defense Research and Engineering, 15 December 1964).

Table I. PROJECT HINDSIGHT WEAPON SYSTEMS

| Designation | Type of weapon system |
|---|---|
| HOUND DOG | Air-to-Surface Missile |
| BULLPUP | Air-to-Surface Missile |
| POLARIS A-1 | Submarine-Launched Ballistic Missile |
| MINUTEMAN I | Intercontinental Ballistic Missile |
| MINUTEMAN II | Intercontinental Ballistic Missile |
| SERGEANT | Tactical Ballistic Missile |
| LANCE | Tactical Ballistic Missile |
| Mark 46 Mod 0 | Antisubmarine Torpedo |
| Mark 46 Mod 1 | Antisubmarine Torpedo |
| M-102 | 105mm Howitzer |
| FADAC | Field Artillery Data Computer |
| AN/SPS-48 | Surveillance and Acquisition Radar |
| Mark 56 | Sea Mine |
| Mark 57 | Sea Mine |
| Starlight Scope | Passive Night Vision Device |
| C-141A | Strategic Transport Aircraft |
| Navigation Satellite | Low-Earth-Orbit Satellite |
| M-61* | Nuclear Warhead, General-Purpose Bomb |
| M-63* | Nuclear Warhead, Missile |
| XM-409 | 152mm HEAT-MP Cartridge, Ammunition for SHILLELAGH Antitank System |

Note: *Data on these two systems are insufficient to warrant their inclusion in all analyses.

(3) Determine significant management and other environmental factors, as seen by the research scientist or engineer, that appear to be commensurate with high utilization of research results.

(4) If the findings of the first strategy indicate a significant reliance on new science or technology, devise a value-cost index (or set of indices) which offers a quantitative measure of the return on investment in research, in terms of the enhanced cost-effectiveness of the weapon systems made possible by the purchased knowledge.

2.2.1 <u>First Strategy—Significance of Recent Advances</u>: The findings based on the first strategy were a key to the entire study. To allow making quantitative measures within the other strategies, it was necessary to establish the general dependence of new weapon systems upon new science or technology and, even more important, to identify the specific contributions of research that were used. The pilot studies had defined three of the critical factors influencing the probability of success in this task and had strongly suggested a fourth.

The *first critical factor* was the recognition that the contributors of scientific or technological knowledge, particularly at the more basic stages, are infrequently aware of many eventual applications of that knowledge. Thus, in order to ensure identification of profitable research, it was necessary to begin the search with the evidence of application to a specific weapon system and then trace backward in time the succession of contributors to the knowledge bank. To this end, 13 weapon systems were selected for analysis in addition to the seven providing the bases for the pilot studies. The total list of weapons and weapon systems is shown in Table I.

The criteria for selection ensured representative samples of as many of the main categories of Defense weapons as possible; wherever practicable, systems having generally comparable predecessors were chosen. No attempt was made to select systems on the basis of suspected high utilization of new technology.

The *second critical factor* identified in the pilot study was the sensitivity of results to the total previous experience of the investigator. In retrospect, the problem is easily understood. The investigator is asked to analyze a system in order to identify the results of recent research. The most practical and efficient basis for the judgments he must make is his own experience. A young scientist or engineer, no matter how brilliant, generally lacks background. This critical factor and the fourth, suspected one were circumvented simultaneously. The pilot studies had suggested that there was reason to believe a contract study group would find its efforts impeded by such matters as proprietary interests within the laboratories of the research performers, the level of its knowledge concerning the management of in-house and contract research efforts of the DoD, and the relatively low degree of private industry's responsiveness to an associate as compared to that shown a Government agency. The adopted solution to both of these problems was

recourse to senior scientific and technical personnel of the DoD, both military and civilian, as investigators.

For 8 of the 13 additional systems, ad hoc study teams were designated by the Assistant Secretary (Research and Development) of the Military Department that developed the weapon system. The principal source of team members was the in-house laboratories. Individuals were selected and teams balanced to ensure the presence of the required technical experience. Each team was responsible for the study of one system, except that in two cases it was found practical for a team to study a pair of systems. On the average it took about three months to study a single weapon system, the cutoff date being primarily a function of the apparent validity and usefulness of the sample of information collected.

In response to the DDR&E's request, the Sandia Corporation undertook studies of two nuclear weapon systems. Conceptually, this effort paralleled the work of the DoD in-house teams, but the 26 RXD Events identified were not reported in as great detail as the primary set of 684 Events described by the Government investigators.

Two system studies were accomplished by the very close involvement of the Deputy DDR&E (Research and Technology), the Director of Project HINDSIGHT, and principal members of the scientific and technological teams that had developed the systems. These weapon systems were relatively small and were somewhat unique in that most of the research and development on both of them was done under the cognizance of one person. As a direct consequence of the meetings between the Project HINDSIGHT principals and the performing groups, utilized scientific and technological advances were identified. A professional technical editor followed up the meetings to collect detailed information on those RXD Events.

The other group studying two systems was made up of scientists and engineers from the industrial organizations that participated as prime contractors in the development of the weapon systems. The anticipated difficulties, as described in the introduction to this report, were encountered. It appears to be reasonably well established that this type of study must be made by DoD in-house people, either ad hoc teams or assigned personnel; each of these alternatives offers some obvious advantages.

The *third and final critical factor* was the operational definition of a discrete scientific or technological advance. The definition had to be used by a number of independently operating investigators with some assurance that each, upon identifying the same advance, would develop a mutually corresponding description. Because the advance identified would eventually serve as the basis for management studies, it was desirable that the activity described be of sufficiently short duration that a single manager or fiscal policy would be involved and the research performers would be readily identifiable.

To these ends, the RXD Event was established. It is defined as the occurrence of a novel idea and the subsequent period of activity during which the idea was subjected to initial examination or test. The RXD Event differs from otherwise similar human endeavors solely in that the testing or examination is primarily a scientific or technological exploration. A more detailed definition of the RXD Event is given in Appendix B, which also defines "interface activity," the process by which knowledge generated in an RXD Event is transferred from the first innovator to the second—and so to its utilization.

Each team began its study by examining system documentation, analyzing system design and details of major components and subcomponents, and discussing technical matters with the weapon-system development engineers to obtain clues to the possible use of new science or technology. Each clue then became a trace initiator; and, to the greatest extent possible, the current user of the item was asked to identify his source document or individual. Then the source was interviewed for the same information, and the process was repeated until the historical trace of the central concept terminated with the discovery of the originator(s). Upon the location of the initially responsible person, the period of the RXD Event was defined, and the required information was collected and displayed as shown in Appendix C.

To minimize the reporting load on the investigators, ensure an even writing quality, and provide a check on the relative completeness of detail in each Event description, a single technical-editing service was established. The technical editor was also responsible for converting quantifiable information to a punched-card format, which facilitated data processing, and for collecting biographical résumés from the people identified as participants in the RXD Events. In the latter effort, the technical editor was supported and assisted by members of the study teams.

At the conclusion of its investigation, each study team prepared a summary report, which serves two functions: First, it highlights the team's observations regarding management, fiscal, environmental or technological factors that appear to be associated with the conduct or support of the utilized research or the transfer of research results to application. Second, it presents a crude measure of the consequence of using new science or technology in terms of increased cost-effectiveness of the studied system as compared to that of its predecessor. These reports, whose security classification varies from open to Secret, have been given limited distribution within the DoD.

2.2.2 <u>Second Strategy—Proportion of New Technology Financed by the DoD</u>: The second strategy of Project HINDSIGHT was to determine the proportion of the new technology on which new systems were based that was a result of DoD-financed research in science and technology. The information needed for these analyses was collected in the course of preparing the RXD Event descriptions. In most cases the general source of financial support for the research worker could be readily determined.

Table II. CLASSES OF RESEARCH AND EXPLORATORY DEVELOPMENT SUGGESTED IN PROJECT HINDSIGHT

| | RXD Class |
|---|---|
| Science | Investigations in pure and applied mathematics and theoretical studies concerning natural phenomena (R). |
| | Experimental validation of theory and accumulation of data concerning natural phenomena (R). |
| | Combined theoretical and experimental studies of new or unexplored fields of natural phenomena (R). |
| Technology | Development of a new material necessary for the performance of a function (XD). |
| | Conception and/or demonstration of the capability to perform a specific elementary function, using new or untried concepts, principles, techniques, materials, etc. (XD). |
| | Theoretical analysis and/or experimental measurement of the characteristics or behavior of materials, equipment, etc., as required for design (XD). |
| Engineering | First demonstration of the capability to perform a specific elementary function, using established concepts, principles, materials, etc. (XD design). |
| | Development of a new manufacturing, fabrication or materials-processing technique (XD mfg.). |
| | First development of a complete system component, equipment or major element of such equipment, using established concepts, principles, materials, etc. (AD). |

Notes: R - research
XD - exploratory development
AD - advanced development

In relatively few cases, about 9.5 percent, the work had been charged to an industrial R&D or overhead account and records were not available or were inadequate to define funding input to the accounts. Where this occurred, and in the interests of conservatism, it was arbitrarily held that the funding was not the DoD's, even though it might have been recovered under ASPR-XV IR&D (i.e., the provision in the *Armed Services Procurement Regulation* governing independent research and development).

2.2.3 <u>Third Strategy--Factors in the High Usage of Research Results</u>: The third strategy was to determine management and other environmental factors that appear to be uniquely correlatable to high utilization of research results. Based upon the recognition during the pilot studies that investigative efficiency was extremely sensitive to the experience of the investigator, it was assumed that a similar situation would obtain in the study of management factors. For this reason, relevant experience was sought and contract assistance obtained from two universities that have active management staffs in their science departments.

The university people were asked to draw upon their experience for hypotheses concerning the relationship between the environment and the probability that research results would be used. They were also asked to design experiments to test these hypotheses, using the identified RXD Events as test cases for the experiments.

By October 1965, several hundred RXD Events had been cataloged. About half of them had taken place in a rather small number of laboratories or other organizations, while the other half was spread over almost as many organizations as there were Events. In the interests of economy alone, it was obvious that a sampling study would have to suffice. Events were categorized by their contributing organization, of which the 10 most prolific were:

Raytheon Company
Ling-Temco-Vought, Inc.
Rocketdyne Division, North American Aviation, Inc.
Lockheed-Georgia Company
Pratt & Whitney Aircraft Division, United Aircraft Corporation
U.S. Army Missile Command, Redstone Arsenal
U.S. Naval Ordnance Test Station
U.S. Naval Ordnance Laboratory, White Oak
Wright Air Development Center
U.S. Army Munitions Command, Picatinny Arsenal

Because it was sensitive to the systems that had been studied, the selection did not necessarily indicate the relative quality of the organizations; but it did provide an efficient way of economically maximizing the sample size for detailed management studies.

In November 1965, these 10 organizations were asked to participate in Project HINDSIGHT by making available a resident management scientist

Table III. UNDIRECTED RESEARCH

1. Observation of phenomena.
2. Formulation of hypothesis.
3. Design of experiment to test hypothesis.
4. Conduct of experiment.
5. Analysis and interpretation of results within the scientist's frame of reference.
6. Report to the scientific community.

Table IV. DIRECTED RESEARCH

1. Statement of problem.
2. Morphological survey of available and apparently relevant knowledge for a possible solution, or deliberate search for new knowledge leading to a proposed solution.
3. Design of experiment to test proposal.
4. Conduct of experiment.
5. Analysis and interpretation of results within the frame of reference of the problem.
6. Report to the "source" of the problem.

to conduct on-site experiments designed by the universities. Recourse to resident management scientists was considered desirable for at least three reasons. First, the individual's knowledge of his organization and its people could save a considerable amount of study time. Second, management would be assured that proprietary interests were protected. Third, because the designated management scientists would not be introduced to the test hypotheses until after the experiments were conducted, bias would be minimum.

By December 1965, one of the universities had conducted brief courses of instruction to familiarize the resident management scientists with study objectives and the proposed methodology. Distribution of test instruments began in January 1966; the collection and analysis of data are expected to continue well into 1967. Primary analysis is the final responsibility of the supporting universities. Their reports will be collected, collated, credited and published by the Project HINDSIGHT office.

2.2.4 Fourth Strategy—Value-Cost Index: The fourth strategy called for defining a value-cost index, or set of indices, offering a quantitative measure of the return on investment in research. From the beginning, this was recognized as the most difficult task undertaken by Project HINDSIGHT. Because the econometrics of the detailed studies was foreign to most of the scientists and engineers identifying the RXD Events, the conceptual cost-value studies were assigned to separate groups. At the time this report was prepared, however, significant progress had not been made.

2.2.5 Definition of Terms: During the pilot studies it was discovered that the current DoD definitions of research (R&D category 6.1), exploratory development (6.2) and advanced development (6.3) were inadequate for use in recognizing, classifying or administering research in science or technology. A more useful classification scheme (see Table II) was gradually developed during the pilot studies and, on the initiation of Project HINDSIGHT, was adopted without change. The successful application of this classification system throughout the studies has demonstrated its utility.

Although adequate to provide a functional description of the several classes of research in science and technology, this categorization did not serve as a vehicle for identifying motivational factors. Further, it was obvious almost from the initial collection of data that the problem of semantics could represent a formidable barrier in the description of scientific research activities. Solely to minimize the impact of this difficulty, definitions were adopted for two terms used in this report: (1) undirected (or disassociated) research and (2) directed (or responsive) research.

The definitions, shown in Tables III and IV, are arbitrary, and are recognized as describing only the two ends of the spectrum. For purposes of Project HINDSIGHT, however, they were found operationally useful, and so are used as a frame of reference in the pertinent data analyses.

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## 3. THE SYSTEMS STUDIED

It was obvious that the selection of weapon systems and military equipments for study under Project HINDSIGHT would influence the findings. The nature and extent of this influence, however, could not be assessed without prejudging the eventual findings.

For example, the greater part of the Army's weapons inventory consists of relatively ordinary items such as rifles, howitzers, tracked and wheeled vehicles, radios for short-range communications, and the like. For most Army operations, these equipments are at least as important as the more "glamorous" guided missiles and tactical nuclear warheads. If it were a fact that, for the former class of weapons, the scientific and technological base came from the general civilian economy and that, for missiles and warheads, it was the result of military-supported research, any undue attention to either class in the HINDSIGHT study would lead to distorted findings.

In a similar vein, if little or no new science and technology were going into modern rifles, howitzers, mortars, trucks, etc.—a situation that seemed rather unlikely but could not be arbitrarily ruled out before the study began—then any findings based on studies of satellites and advanced radars would not be amenable to extrapolation or other statistical inference. To ensure that the findings would be reasonably valid, HINDSIGHT had recourse to a sampling technique for system selection, not a truly random sample, but a controlled one to achieve an apparent balance of equipment types.

The weapon systems and equipments that served as the basis for this study (see Table 1) are briefly described in the following pages.

### 3.1 HOUND DOG

HOUND DOG is a jet-propelled air-to-ground missile with a nuclear warhead and a stellar-monitored, all-inertial guidance system. It is air-launched from a pylon beneath the wing of a B-52 aircraft. The missile operates in either a high subsonic or a supersonic mode and has an operating range in excess of 350 nautical miles.

Weighing approximately 12,000 pounds, the missile has delta planform wings in a canard arrangement; the wing is located well aft on the fuselage and the horizontal stabilizer is placed at the nose. The fuselage, an ogival nose faired into a long cylindrical afterbody, contains the guidance package, the warhead and all other subsystems, except that the power plant is suspended far aft in an engine nacelle beneath the fuselage.

Development of HOUND DOG began in 1956 and was essentially complete in 1959.

### 3.2 BULLPUP

BULLPUP is an air-to-ground missile, optically tracked and radio-command-guided, intended for use against tactical targets such as trains, bridges, tanks, truck convoys, ships and ground weapon emplacements. Aerodynamic control surfaces are on the nose of the missile (canard configuration), and delta wings provide primary aerodynamic lift. This uncomplicated, relatively inexpensive weapon has a designed maintenance-free shelf life of 5 years and can be loaded on an aircraft in minutes with no checkout or other ground support.

Different versions of the BULLPUP missile use either a solid-propellant or a prepackaged liquid-propellant rocket motor. The smaller BULLPUP A can deliver a 250-pound conventional warhead over a range up to approximately 6 miles from the point of release by the launching aircraft. The larger BULLPUP B carries a 1000-pound conventional warhead over a range of some 9 miles.

In operation, the pilot of the launching aircraft monitors the missile in flight by radio and controls its path by keeping flares in the missile's tail lined up with the target.

Development of BULLPUP A was initiated in 1954 and led to a first production run in early 1958. The first production contract on BULLPUP B was awarded in 1960.

### 3.3 POLARIS A-1

POLARIS A-1 was the first of the series of submarine-launched, inertially guided, intermediate-range ballistic missiles. The A-1 was small in comparison to contemporary missiles of equivalent range, could be launched from a submerged submarine, and had high inherent reliability and relatively low maintenance requirements.

Its solid-propellant rocket motors were capable of delivering a nuclear warhead over ranges well in excess of 1000 nautical miles with an accuracy commensurate with the navigational precision of the launching submarine.

Despite the important increase in combat potential offered to the fleet by the introduction of POLARIS A-1 in 1960, the system's development had exploited surprisingly little really new technology, especially in view of the relatively much greater amount that was used in the A-3 version. Undoubtedly this was partially a consequence of the A-1's very tight development schedule, which allowed no freedom for long-lead-time efforts. Pre-1945 torpedo-launch technology was the chief basis for the launch-tube mounting and missile-ejection system; a portion of the missile's suspension, or shock-mitigation system was developed from aircraft arresting-gear technology; the inertial guidance system, computer technology and the nuclear warhead were no doubt state-of-the-art developments.

The compressed development time of the POLARIS A-1 is indicated by the fact that not until April 1957 were decisions made regarding the principal technical guidelines, yet a POLARIS submarine was at sea in June 1960—a full 5 years ahead of the initial target date set in 1955.

### 3.4 MINUTEMAN I and II

MINUTEMAN is a 3-stage, solid-propellant, all inertially guided intercontinental ballistic missile. Project HINDSIGHT examined the technology leading first to MINUTEMAN I and then to its successor, MINUTEMAN II. This was done in an attempt to gain some understanding of how much new science and technology are involved in the marked upgrading of functionally quite similar systems.

The MINUTEMAN missile is about 55 feet long, reaches a velocity of over 15,000 miles per hour in flight, and has a range of over 5000 miles. Motors of the first two stages are in metal cases, while the third-stage motor is encased in fiberglass.

The inertial guidance system is a highly accurate arrangement of gyroscopes running on practically frictionless bearings. A digital computer contains a memory section which stores the missile's flight program. During flight, the computer serves to compare the achieved flight profile with the stored program, calculate steering corrections so as to maintain the desired trajectory, and send signals to the nozzle steering system to keep the missile on course.

A reentry system contains the fuzing mechanism and the nuclear warhead.

A steel-lined concrete launch tube 80 feet deep houses the missile. Surrounding the launch tube, under several feet of concrete, is a two-level equipment room that is reached through a hatchway with a hydraulically operated cover. This room contains systems for communications, launch control and monitoring, and electric-power conversion and distribution. Additional equipment required for normal operation of the launcher is installed in a launch-support building a short distance away.

### 3.5 SERGEANT

This tactical Army missile can carry either a conventional high-explosive or a nuclear warhead up to a maximum range of approximately 75 miles. The 35-foot solid-propellant missile is fired from a mobile launcher and is inertially guided to the target. Because of its high thrust-to-weight ratio, SERGEANT requires no booster.

For mobility in the field, the SERGEANT missile is transported in sections on conventional Army trucks that have been slightly modified to accommodate the system. The warhead is carried in its own van, and the motor, guidance and stabilization-fin sections are moved on a semitrailer. When a missile is to be fired, a suitable launching site is selected and

the principal vehicles are driven into position. Emplacement, missile assembly, checkout and preparation for firing can be completed in a matter of minutes.

Development of SERGEANT began in 1954, and production commenced in 1960. It was one of the first systems to employ a modular design concept. When a malfunction is detected during checkout, the failed component is simply unplugged and a replacement assembly inserted.

### 3.6 LANCE

LANCE, another tactical Army missile system, is being developed as an artillery-guided weapon to support the field army division. This 3200-pound missile is intended to carry a nuclear, conventional high-explosive or chemical warhead over a considerably shorter range than SERGEANT's 75 miles.

The propulsion system uses prepackaged storable hypergolic liquid propellant, which enables the same instant readiness provided by solid fuel, but also offers simplified variable boost and thrust termination for improved accuracy. LANCE is guided by a unique inertial reference and automatic meteorological correction scheme. The missile is directionally controlled by steering the rocket exhaust.

The LANCE missile is about 20 feet long, and its cylindrical body is about 22 inches in diameter. It is stabilized by cruciform clipped delta fins with an overall span of about 4 feet.

Among other components of the LANCE system are a self-propelled launcher, convertible to a lightweight towed launcher, and a self-propelled missile transporter-loader. With this equipment, LANCE will have cross-country mobility and will be deliverable by fixed- or rotary-wing aircraft and by parachute as well.

### 3.7 Torpedoes Mark 46 Mod 0 and Mark 46 Mod 1

These torpedoes are antisubmarine weapons designed to attack targets at all operational depths. About 9 feet long and slightly over a foot in diameter, both torpedoes can be delivered by either aircraft or surface vessels. They have essentially the same self-contained guidance system, which enables the torpedo to locate and attack targets within its search volume with no external assistance. Warheads in both cases are conventional high explosive.

Primary technical differences in the torpedoes are found in their engines and steering concepts. The Mod 0 uses a solid-propellant fuel to drive a hot-gas engine; the Mod 1 has a liquid-monopropellant cam-engine propulsion system. Control in the pitch and yaw planes for the Mod 0 torpedo is achieved by tilting a shroud ring that encompasses the counterrotating propellers. Roll control is provided by fin tabs. The Mod 1 uses movable fins for control in all planes.

Development of the Mod 0 was undertaken in 1958, and first deliveries to the fleet were made in 1963. Because it uses many of the proven components of the Mod 0, the Mod 1 development, which started in 1963, was completed in about 2 years.

## 3.8 105mm Howitzer M-102

This howitzer was designed for the role of a conventional light artillery piece, although many of its characteristics are unconventional. Most artillery pieces, once emplaced in firing position, have a limited ability to traverse in azimuth (typically on the order of 60 degrees) but the M-102 can traverse a full 360 degrees. In addition, improved steels were used in the construction of barrel and breech, which permits higher internal pressure and thus a considerably greater range than its 105mm predecessors.

In spite of these advances, the weight of the entire howitzer was kept low enough to permit transporting it by helicopter.

Early models of the M-102 were made available to the Army in 1962.

## 3.9 FADAC

The field artillery data computer (FADAC) is a general-purpose digital computer that has been designed and tailored to assist the artilleryman in the solution of fire-control and survey problems.

Classified by the Army as a standard equipment in 1961, this computer can be used with all classes of artillery and a number of the Army's missiles, including LANCE.

FADAC is about 12 inches high, 27 inches wide and about 30 inches deep, and weighs approximately 190 pounds. Despite its small size, the magnetic-disk primary memory unit has a capacity of 8192 words.

## 3.10 AN/SPS-48 Radar

This system represents an answer to the current fleet requirement for a practical "3-D" radar capable of simultaneously performing multiple functions, such as air surveillance, control of aircraft intercept, target designation for weapon-control systems, and provision of information for use in evaluating the air battle. Earlier radars were limited to providing information in only two of the three coordinates—azimuth, elevation and range; the designation "3-D" indicates the added three-dimensional capability of this new radar.

The antenna of the AN/SPS-48 is mechanically rotated in the horizontal plane to acquire azimuth information. A 9-pencil-beam pattern in the vertical plane, with electronic switching, provides elevation data. The radiating elements are windowed slots in the transverse wave guides making up the planar array antenna. The array is end-fed by a serpentine wave guide.

The radar was designed primarily for installation on guided-missile frigates and destroyers. It is computer stabilized to remove perturbations in data arising from ship's pitch and roll.

The Navy's development of the SPS-48 began in the early 1960s. A production model was installed in the USS WORDEN during the first half of 1965.

3.11 Mines Mark 56 and 57

The Mark 56 is an aircraft-laid moored mine in the 2000-pound class, designed for employment against submarines. The Mark 57 mine is its submarine-laid counterpart. Both use conventional high-explosive warheads.

Conceptually, these weapons are not significantly different from their predecessors of World War II. Because of advanced design details, new materials and recent technological developments, however, they offer considerably increased lethality, sensitivity and resistance to countermeasures, the ability to operate at much greater depths, increased shock resistance to airdrop, and much greater overall reliability.

The major differences in the two mines lie in their markedly individual means of deployment—the Mark 56 from the wing of a high-performance aircraft, the Mark 57 from a submarine's torpedo tube.

The current version of the Mark 56 mine was released to production in 1963; production of the Mark 57 started 3 years earlier, in 1960.

3.12 Starlight Scope

The Army's Starlight Scope is a night-vision device that can be either hand-held or mounted on a tripod for use in observation and surveillance when it is too dark to see with the naked eye. The instrument, which looks much like a telescope or a rifle scope, can also be mounted on weapons to enable aiming at night.

This passive device employs the principle of image intensification to raise the light level in the viewed scene above the human eye's level of sensitivity. It was released to field use in 1965.

3.13 Strategic Transport Aircraft C-141A

The C-141, a 4-jet-engine aircraft with a crew of 8 men, was designed to airlift all the military services' combat or support units and military supplies, delivering them by landing or by parachute, as required. It can carry 154 soldiers with their individual equipment or 80 litter patients and 8 attendants. Alternatively, it can carry about a 31-ton payload over 4000 nautical miles at an average speed of 422 knots.

The aircraft is 145 feet long, has a wing span of approximately 160 feet and a maximum height of almost 40 feet. Its service ceiling is over 44,000 feet. Maximum speed at an altitude of 25,000 feet is about 500 knots.

The letter contract authorizing the development of the C-141A was dated April 1961, and the aircraft saw its first service in October 1964. A unique aspect of its development was that the initial contract required the aircraft to be certifiable by the Federal Aviation Agency for commercial use in addition to satisfying military requirements.

### 3.14 Navigation Satellite

This artificial satellite, launched into a low earth orbit, makes it possible to determine a ship's position accurately regardless of weather or the anomalies of low- and medium-frequency radio propagation.

By monitoring the Doppler shift in the ultra-high-frequency signal emitted by the satellite, the navigator can determine the instant of the satellite's closest approach to his location and the slant range between the two points. Using time-reference information in the radiated signal and published data on the satellite's orbital parameters, he can compute his position precisely.

The concept of a navigation satellite appears to have been considered seriously in late 1957 or early 1958. In September 1963, a satellite was actually used in ship navigation. The first truly operational navigation satellite was placed in orbit on 6 December 1963, providing the U.S. Navy with the most reliable, precise all-weather global navigation system ever developed.

### 3.15 Nuclear Warheads M-61 and M-63

These nuclear warheads, now being introduced into the weapons inventory, are advanced versions in comparison to their predecessors. They use nuclear material more efficiently, have improved structural and mechanical features, and possess greater adaptability to design constraints imposed by the weapon-delivery system.

Because of security restrictions, the warheads cannot be more completely described here; those considerations also preclude subjecting them to the same type of study as that adop~~d for the other weapon systems surveyed under this Project.

The study of the M-61 and M-63 nuclear warheads was limited to a sampling of RXD Events that the study team believed to be generally typical of advances in the non-nuclear components of nuclear warheads. The samples were small and contained less detail than those of the other 18 systems studied.

3.16 152mm HEAT-MP Cartridge XM-409

The Sheridan is a new armored reconnaissance vehicle developed by the Army to replace the post World War II light tank. Its main armament features a 152mm gun-launcher that fires either the highly accurate anti-tank SHILLELAGH guided missile or a relatively unconventional artillery projectile. The complete artillery round of which that projectile is a part is the 152mm HEAT (high-explosive antitank) MP (multipurpose) cartridge XM-409. The "MP" designation means that the ammunition can defeat both hard and soft targets.

The cartridge case, which is completely consumed within the gun barrel when the round is fired, is a two-piece assembly, manufactured by a felting process from nitrocellulose and Kraft fibers with a resin binder. The projectile consists of a one-piece forged-steel body which is loaded with approximately 6.5 pounds of Composition B. The high-explosive charge is shaped so as to provide, on being fired, an extremely intense focused jet of energy; this represents the weapon's antitank kill mechanism. Fragmentation of the projectile's steel body provides the capability for defeat of soft targets.

# 4. PRINCIPAL FINDINGS

The general objectives and strategies of Project HINDSIGHT were described in section 2, and some additional specific questions to which the study was addressed were set forth in the introduction. The findings of this Project, in terms of those general objectives, strategies and specific questions, are presented in this section.

The study approach adopted for Project HINDSIGHT is such that, in the purist's sense, the findings frequently are indicative rather than conclusive. This acknowledgment in no way weakens the significance of the findings, but recognizes only that the complexity of the processes studied is so great as to preclude an exhaustive understanding. More specifically, it concedes that a great variety of management patterns have been shown, by at least one example, to be workable. Nevertheless, the HINDSIGHT data indicate that some patterns, by the frequency of their appearance, are more likely to be associated with research efforts whose results are utilized.

Whenever possible, data are presented as time-dependent distributions, or as percentages of a total, to afford an estimate of the relative degree of confidence that may be assigned to the validity of the indication or finding.

In some cases, interpretation of findings was found to be extremely sensitive, either to the precision with which certain words are defined or to the manner in which those words are used. This problem was encountered early in the study, and operationally useful definitions were invented or adopted. As pointed out in section 2, the most sensitive areas involved—

. the general classification scheme for RXD Events and

. the delineation of basic research in science undertaken to satisfy the curiosity of the scientist, as distinguished from that undertaken for more pragmatic reasons.

Classifying the sources of new scientific or technological knowledge in terms of organizational type—DoD laboratories, universities, industries—presented no especial problem, except that it failed to provide insight into the motivation of the performers. To overcome this weakness, an additional classification scheme was adopted which divides all research into two categories. One, referred to in this report as undirected (or disassociated) research, is conceptually described in Table III; and the other, termed directed (or responsive) research, is described in Table IV. These definitions, or categorizations, provide a frame of reference for pertinent analyses and discussions.

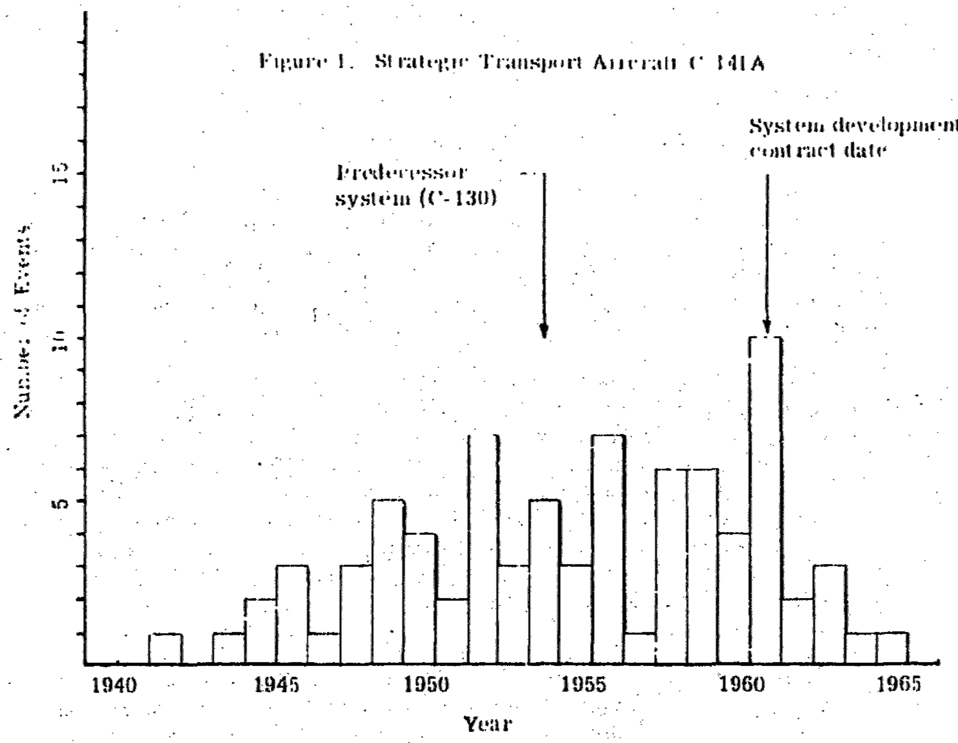


Figure 1. Strategic Transport Aircraft C-141A

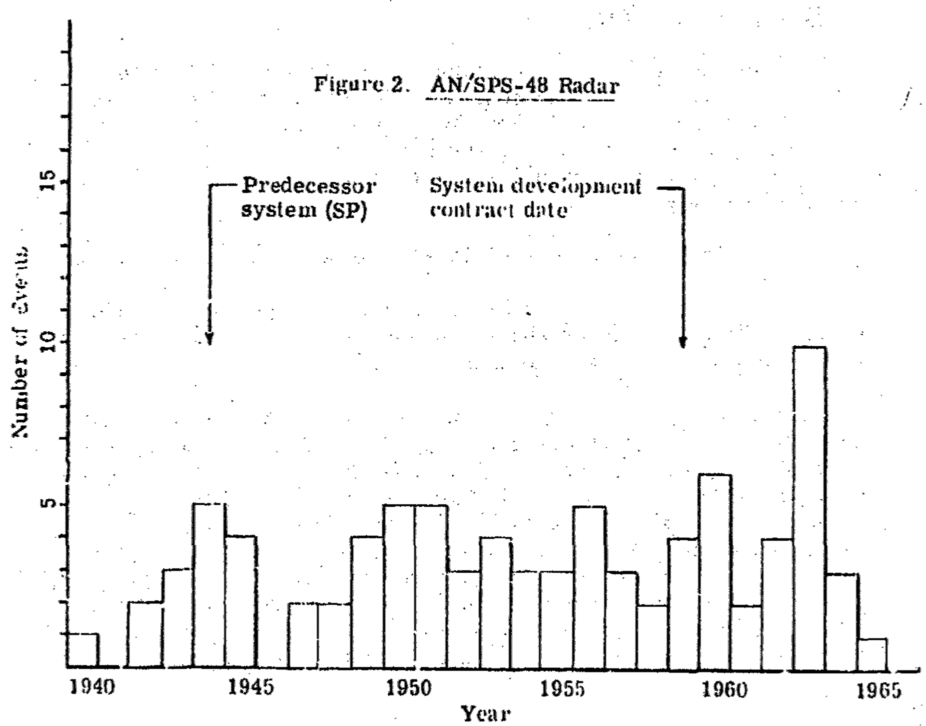


Figure 2. AN/SPS-48 Radar

4.1 First Strategy: Determine the extent to which new weapon systems are actually dependent upon the results of *recent advances* in science or technology for their attained increase in system effectiveness, decrease in cost, or increase in cost-effectiveness as compared to a predecessor system.

4.1.1 Finding: *Markedly improved weapon systems result from skillfully combining a considerable number of scientific and technological advances.*

A very early observation of the Project HINDSIGHT study was that, almost without exception, no single identified RXD Event or combination of a very few Events is responsible for an appreciable portion of a total advanced capability. It is most unlikely that the observation would hold true throughout a study of the first atomic-fission bomb, wherein a relatively small number of very significant Events involving Einstein, Fermi and a few other physicists apparently account for that capability. The observation, therefore, is generally limited to cases in which the predecessor and successor systems were technologically similar but unequal in cost-effectiveness. Even here, however, there are apparent exceptions, as in the case of the modern artillery howitzer. This seeming discrepancy is treated later in the discussion of findings 4.1.2 and 4.1.3.

The time distributions of the RXD Events, with regard to the dates of decision to undertake engineering development of the particular weapon systems in which the new science or technology was used, form illuminating patterns. Representative distribution curves are shown in Figures 1 through 11 and are discussed in subsequent findings.[3]

4.1.2 Finding: *There is a high positive correlation between the relative sophistication of the predecessor and successor systems—or the relative increase in their effectiveness—and the amount of new science or new technology utilized in the successor.*

The argument for this finding requires the appreciation of two background factors: (1) the number of RXD Events that would probably have been disclosed by a more exhaustive treatment and (2) a measure of the relative value of each Event.

Figures 1 through 11 represent the RXD Events that were actually investigated in detail. Estimates of the percentage of coverage range from 20 percent for the C-141A aircraft to 40 percent for the AN/SPS-48 radar, 75 percent for LANCE, and over 95 percent for the Mark 56 and 57 mines. The spread is a function of many factors. The percentages vary positively with the accessibility of the RXD Event's performers and with

[3]Summary descriptions of these RXD Events and some of the more relevant data are given in Appendix D.

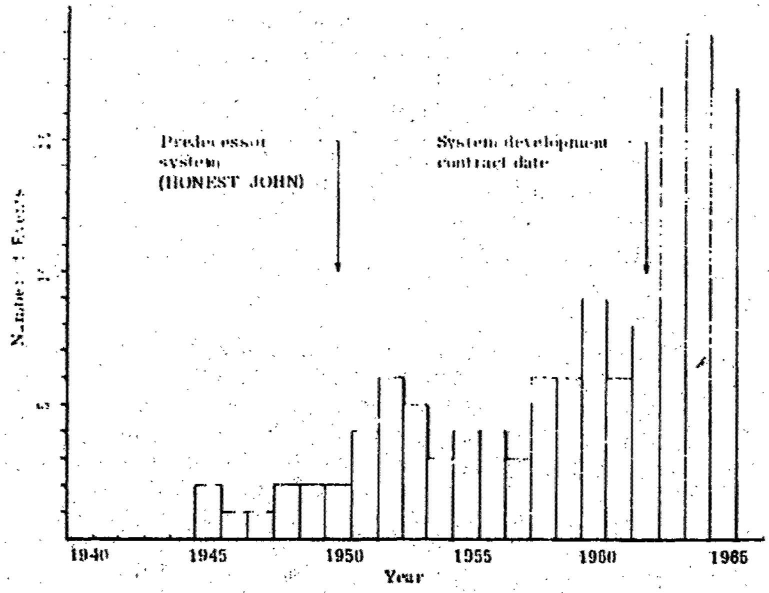
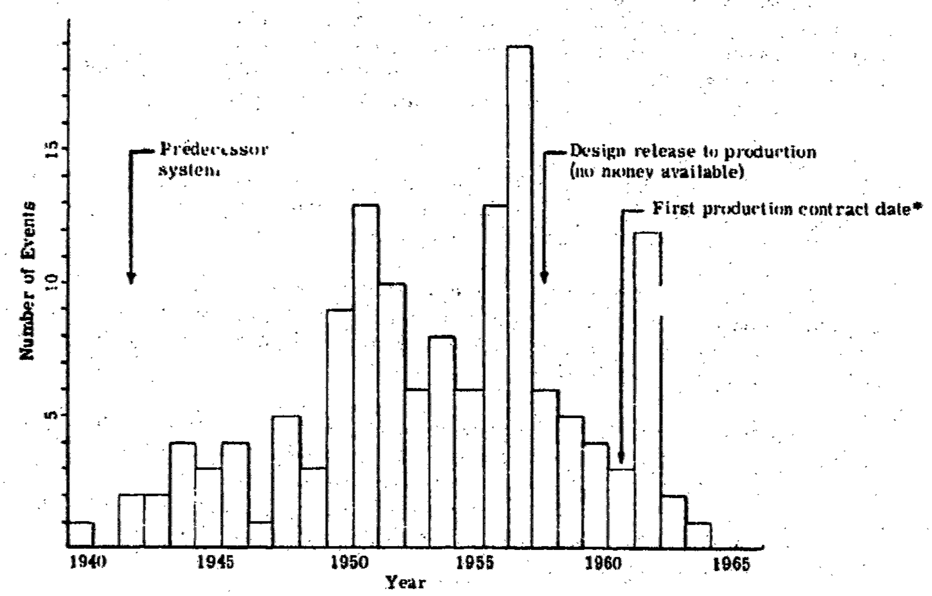



Figure 3. LANCE Missile




Note: *Includes significant specification changes.

Figure 4. Mines Mark 56 and 57

the size and diligence of the study team and, inversely, with the complexity of the equipment studied. To the extent controllable, however, each sample is representative of the overall type of RXD Event culminating in the specific equipment.

Studying a relatively small number of Events that were sequentially related in a single scientific discipline or area of technology was generally preferred to pursuing many tentatively identified Events across a broad spectrum of technologies. Thus, there could be up to five times as many Events as have been counted. The distribution among the several classes of research and exploratory development, though, should remain essentially unchanged.

The second factor, justifying all contributing Events as equal in weight, can be supported by a simple illustration. The transistor is generally accepted as one of the most important scientific and technological advances of the current period. Of what value would the transistor be to an ICBM airborne guidance computer if the capacitors were large, leaky, wax-impregnated devices? ...if the inductors and transformers used huge iron cores? ...if the power supplies were lead storage batteries or internal-combustion-engine-driven generators? ...and if the chassis and mechanical support were fabricated of low-yield-strength steel?

Recognizing the part that each advance plays in this mutually supporting effort, one can conclude pragmatically that all utilized Events have essentially equal value in a single weapon system. It is therefore meaningful to compare systems simply in terms of the number of Events required to achieve their demonstrated performance.

The simplest weapon system examined was the M-102 105mm howitzer. This weapon shows an increase in effectiveness over that of its predecessor, the M-2A1, in two significant parameters: To achieve practical transportability by helicopter, it is much lighter in weight, and it offers an approximately 40-percent increase in range. A significant part of of the weight reduction, along with the ability to withstand the higher internal pressure commensurate with the extended range, is attributable to a single RXD Event involving the production of better steel for the gun tube. Most of the remaining weight reduction was enabled by the RXD Event of welding aluminum. A few additional Events involving propellant manufacture and barrel-erosion control provided for the increased range. Thus, starting with a relatively uncomplicated system, a total of five to seven Events resulted in a markedly improved howitzer.

Conversely, for a somewhat comparable increase in effectiveness from MINUTEMAN I to MINUTEMAN II, some 50 technological advances were essential (see Figure 5). Thus, the greater the sophistication of the predecessor, the more new science or technology is required to achieve a useful improvement in cost-effectiveness. Where the predecessor systems were roughly comparable in sophistication (a situation that generally existed for World War II free-fall bombs and magnetic-influence mines), the study's findings suggest that the relative increase in

Figure 5. MINUTEMAN I and II ICBMs

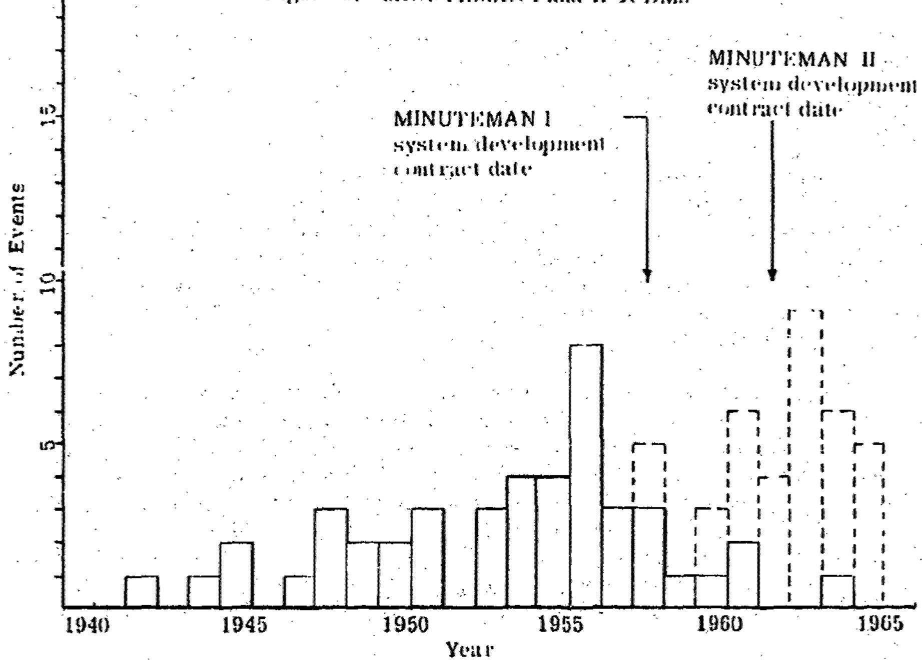
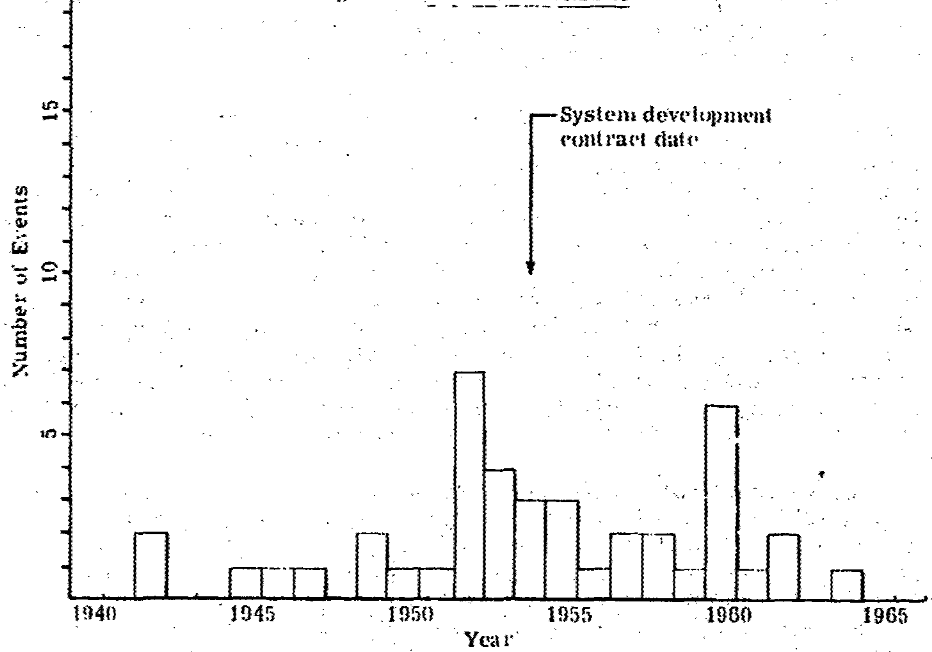



Figure 6. BULLPUP Missile



effectiveness of the successors varies directly with the number of utilized RXD Events.

For example, some 40 to 50 Events were required to achieve an increase by a factor of about 4 between the free-fall bomb and the BULLPUP air-to-surface missile. It took over 100 RXD Events to increase the Mark 56 mine's effectiveness by a factor of 10 over that of the Mark 10 mine. In each case, predecessor and successor are compared only with respect to roles that both could perform.

Other paired examples that indicate the same trend can be cited. The sample size, in terms of number of systems studied, is inadequate to provide a useful quantitative predictor of the number of Events essential for a desired increase in cost-effectiveness. However, crude analysis of the data suggests that such a predictor can be achieved. This matter is treated further in section 7.

4.1.3 Finding: *New weapon systems are more dependent upon the new technology than on new science.*

Mainly, the systems studied were of the post-1945 period.

Project HINDSIGHT adopted flexible criteria for the definition of new or recent technology. If the technology of interest was used in a cruder form in the predecessor system, the evolution of that technology was traced back only as far as the time the predecessor system was developed, generally after 1945. If it was not used in the earlier system, the evolution of the technology was traced back to about 1945. The criteria were relaxed somewhat for new science, accepting some RXD Events that occurred as early as 1935. Despite this double standard, 91 percent of the 710 completed RXD Events are classified as the results of research in technology, the remaining 9 percent, as the results of research in science.

Further, less than 16 percent of the technologically oriented RXD Events were traced to a post-1935 science base. The other 84 percent came directly from the application of nineteenth-century unified theory, were the results of empirical research, or appeared as inventions not needing scientific explanation.

The median cost of a DoD-funded Event of a scientific nature (R) was approximately $60,000; for a DoD-funded Event of a technological nature (XD), the median cost was about $45,000. In view of the differences in cost and the percentage of RXD Events oriented toward science, one possible conclusion is that a budget for research in mathematics and the physical sciences should be about 10 percent of the size of one for research in weapons technology, where the classifications shown in Table II for science and technology (R and XD) describe the total package and where the sole objective is gaining knowledge for application to weapon systems.

Figure 7. HOUND DOG Missile

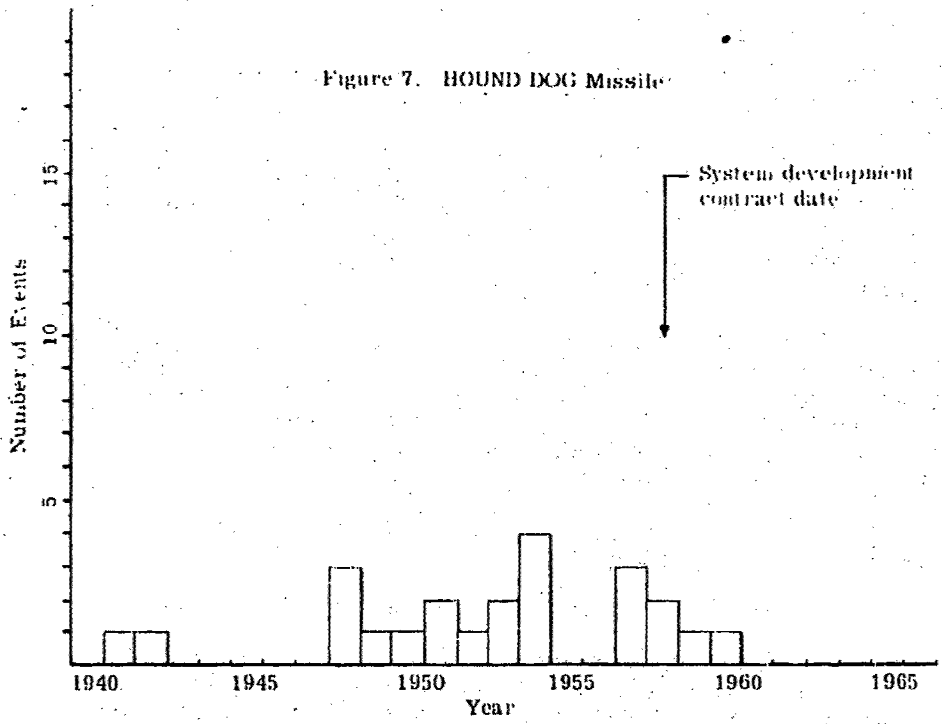
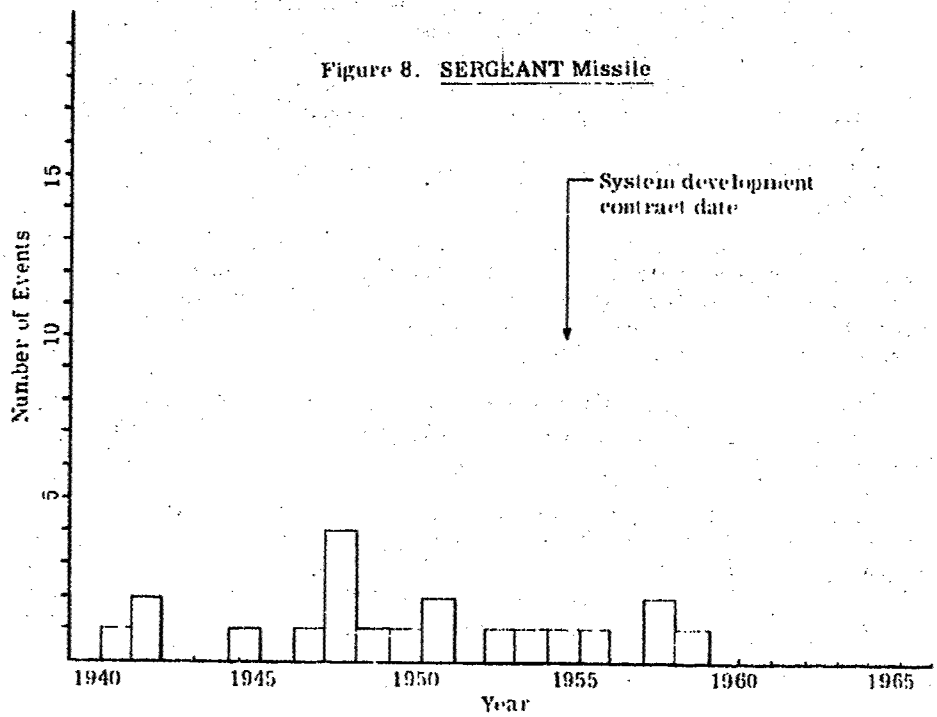



Figure 8. SERGEANT Missile



This conclusion cannot be applied arbitrarily as a test of current DoD fund allocations for at least two significant reasons. First, the conclusion is applicable only where the work efforts are divided in accordance with the definitions of Table II. The most cursory examination of the DoD's current research and exploratory-development project structure shows that a considerable portion of its research efforts are of a generally technological rather than scientific character. Second, the 10-percent factor does not allow for very necessary work in the life, behavioral, social and other sciences.

4.2 Second Strategy: Determine the proportion of any new technology, required for attaining system characteristics, that was the result of DoD-financed research in science or technology.

4.2.1 Finding: *The DoD financed the majority of programs supplying new science or technology for weapon-system improvement.*

Throughout the 1945-1963 period covered by this study, there was almost continuous change in research budgeting, accounting and procurement practices. Records have been retired or lost, and seemingly little attention has been paid to historical accounting for expenditures on research in science or technology. As a consequence, no precise figures exist to describe DoD or other investment in these areas.

A useful estimate can be derived, however, by noting that the FY 1966 Defense budget for these categories of research is $1.39 billion. Using the generally accepted understanding that this investment had been growing at a rate of 8 to 10 percent per year, a total investment of $7.5 to $10 billion for the years 1945-1963 is calculated. A similar calculation suggests that non-DoD funding (including industry, state support of university research, and other Federal agencies' expenditures) came to some $5-7 billion for the same period. These estimates are given primarily to demonstrate the absolute and relative orders of magnitude of expenditures for research within the United States. (See Appendix E.)

For the 710 RXD Events investigated in detail, the distribution of funding sources was as follows:

| | |
|---|---|
| DoD direct funding - - - - - - - - - - - - | 85% |
| Defense-oriented industry - --- - - - - - | 9% |
| Commercially oriented industry- - - - - - | 5% |
| Other Government agencies - - - - - - - - - | >1% |
| Universities (state or private funding) - | >1% |

The 85 percent directly funded by the DoD includes work supported by the in-house laboratories of the Military Departments and all DoD contract and grant-supported work with any external organization. It does

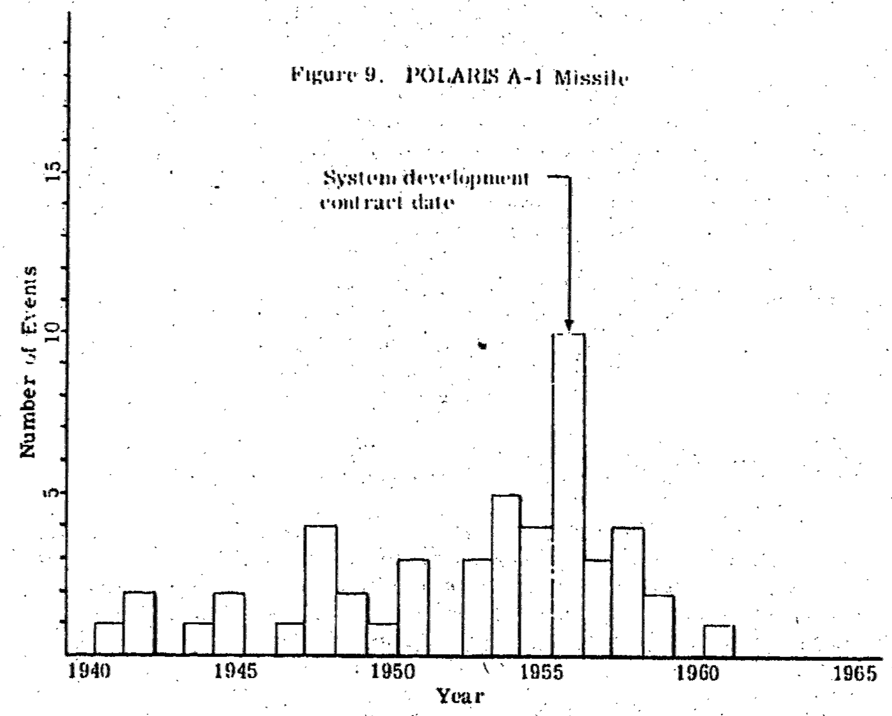


Figure 9. POLARIS A-1 Missile
System development contract date
Number of Events
15
10
5
1940
1945
1950
1955
1960
1965
Year

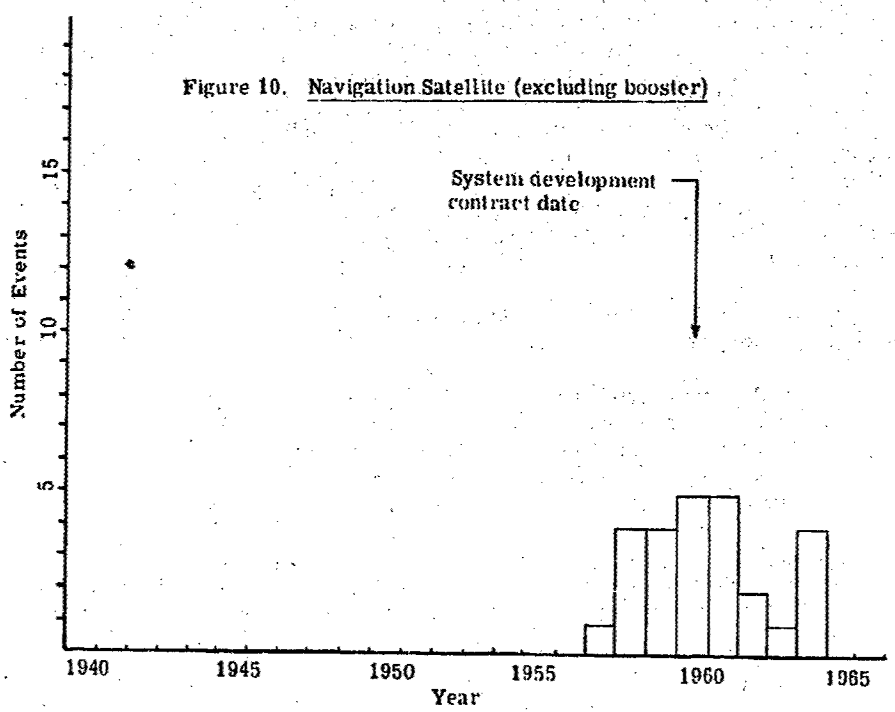


Figure 10. Navigation Satellite (excluding booster)
System development contract date
Number of Events
15
10
5
1940
1945
1950
1955
1960
1965
Year

not include work supported under the ASPR-XV IR&D Program, a funding procedure under which Defense contractors can recover some self-generated research expenses as an overhead cost against DoD contracts; nor does it include work funded by industry out of profits on DoD contracts and initiated for the purpose of gaining future contracts.

Inclusion of the last-named categories suggests that, whereas the DoD only funded an estimated 55 to 65 percent of all on-going research in science and technology, 94 percent of the work that led to results useful in weapon systems was in the class directly or indirectly funded by the DoD.

The principal conclusions that could be drawn from this observation are that DoD requirements are in fact unique or that a tremendous duplication of effort was involved. To a certain extent the latter possibility is refuted by the findings discussed in section 4.3 regarding motivation for utilized research.

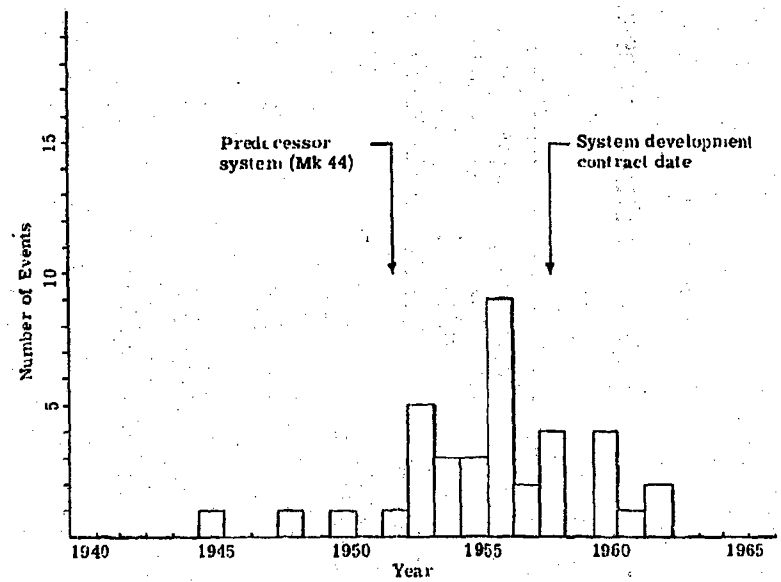



Figure 11. Torpedo Mark 46

Table V. UTILIZATION OF RESULTS OF RXD EVENTS

| Performing agency | Distribution of RXD Events (% total) | NSF* estimate of available funds (% total) | Cost of RXD Events (% total) | Ratio: Percent of Events to-- Percent of funds available | Percent of funds spent |
|---|---|---|---|---|---|
| University (including science and technology centers) | 8.1 | 13 | 12 | 0.6 | 0.7 |
| Industry | 43.8 | 54 | 57 | 0.8 | 0.8 |
| In-house DoD laboratories | 48.1 | 33 | 31 | 1.4 | 1.4 |

Note: *National Science Foundation.

4.2.2 Finding: *The median cost of an RXD Event is essentially independent of the source of funding.*

Within a three-standard-deviation limit, identified costs of DoD-funded Events in the XD category varied between a few hundred dollars and $580,000. The median Event cost was found to be approximately $45,000. Industrially funded Events for the same class of research varied in cost between a few hundred dollars and $250,000, with a median of about $33,000. So few RXD Events were funded by other sources that their analysis would be statistically unreliable.

In the two categories on which useful data exist, the conclusion can be drawn that, although the DoD can or will undertake far more expensive research tasks than industry, the median RXD-Event costs are quite comparable. Accepting the estimate that there is a difference of less than a factor of 2 between total DoD and total non-DoD investment in research, this finding also suggests that the DoD funds a greater percentage of low-cost research than industry does.

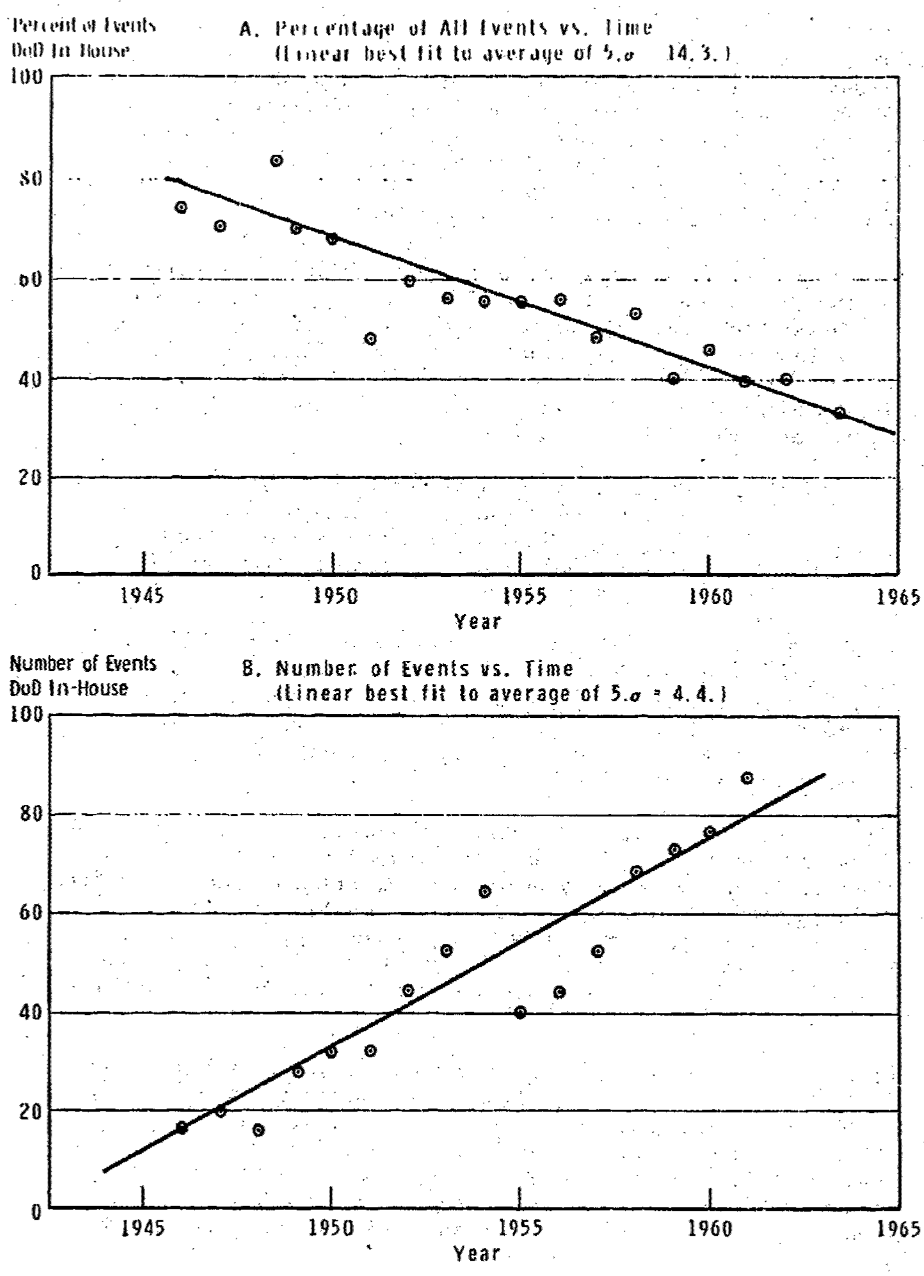
4.3 Third Strategy: Determine significant management and other environmental factors, as seen by the research scientist or engineer, that appear to be commensurate with high utilization of research results.

4.3.1 Finding: *The utilization factor appears insensitive to classical differences in organizational structure or profit motivation appearing between U.S. industry, in-house DoD laboratories, and university-associated science and technology centers. It may, however, be sensitive to differences between these types of organization and the classic organizational structure of universities.*

Within these three major organizational types, the distribution of RXD Events was found to be that shown in column 1 of Table V. The true measure of relative productivity of these three organizational divisions would require that the distribution of RXD Events be compared with the funds available for research in science and technology in the same time period. While data of this type are not available, or are not known to exist in useful form, a less rigorous measure of funding correspondence may be developed.

First, over 91 percent of the RXD Events can be described within the National Science Foundation's "applied research" category; NSF estimates of DoD fund distribution, by type of performing agency, from 1963 to FY 1966 are shown in column 2 of Table V. A second measure of the distribution of funds is available directly from the data gathered under Project HINDSIGHT. Percentages of the total cost of identified RXD Events appear in column 3 of Table V—again, classified by performing agency.

**Figure 12. IN-HOUSE DOD ACTIVITY**



The most immediate observation to be made from Table V is the close correlation between RXD Event and funding distributions for both available and expended fund percentiles, as calculated in columns 4 and 5. The ratios vary only slightly from one organization type to another, partly substantiating the finding. The NSF estimates for 1963-1966 cannot be expected to represent the distribution of funds over the previous 18-year period; however, they provide a useful first-order approximation.

It is the nature of research that dollar amounts convert readily to scientific and engineering man-years, and this allows a second approach to the finding. The total national population of scientists roughly quadrupled during the period from 1945 to 1963, while the same population segment in the DoD laboratories is believed not even to have doubled. If the finding is valid, therefore, the DoD laboratories should show a general decline by a factor of approximately 2 in the *percentage* of RXD Events generated in-house and an increase by the same factor for the *absolute* number generated. Figure 12 displays the time trend of DoD in-house RXD Events, showing very nearly the exact results expected.

Available funding data for universities do not permit an analysis of the relative productivity of two groups of research scientists—those associated primarily with the educational portion of the university and those associated with the scientific and technological centers. Such centers as the Lawrence Radiation Laboratory of the University of California, the Jet Propulsion Laboratory of the California Institute of Technology, and the Instrumentation Laboratory of the Massachusetts Institute of Technology are currently receiving an amount estimated at less than 25 percent of all funds for basic and applied research going to the entire university class—and, of this, perhaps 60 percent is for applied research. Comparatively recent increases in the size and number of these groups suggest that their earlier funding was even less. Thus, it is significant to find that 75 percent of the university-credited RXD Events came from associated science and technology centers or arose out of recognizably mission-oriented programs.

Within the correlation accuracy of the sets of figures cited and modified by the discussions, it is concluded that the utilization of research results is essentially insensitive to differences in classic organizational structure that may appear in U.S. industry, in-house Defense laboratories, and university-associated science and technology centers. The finding cannot be extended to include the educational portion of a university.

4.3.2 Finding: *[illegible]*

To the extent permitted by the accessibility of the research performer and the validity of his recall, information was sought regarding his original motivation. Less than 2 percent of the RXD Events classified as research in science—that is, less than one-half of 1 percent of the total—appear to have come about because the performer was interested primarily in extending the bounds of knowledge. In 98 percent of the scientifically oriented Events, the scientist appears to have been motivated chiefly by his awareness that an actual problem existed.

For this particular analysis, a distinction was made, not between basic and applied research in science, but between undirected (by an agency external to the performer) and mission-oriented research. The criteria for classification included the requirement that the performance be associated with an identifiable generic problem rather than some vague possible utility of the result. Thus the data are considered reasonably representative of the situation.

The distribution within the mission-oriented 98 percent shows that 73 percent was funded by the DoD, 19 percent by industry, and 8 percent by other Federal agencies or by foreign governments. Within the 73 percent funded by the DoD, 21 percent of the work was done as part of an organized program at a university-operated science and technology center, 12 percent as a separately funded project at a university, and 38 percent at in-house DoD laboratories; and the remaining 29 percent was done by industry.

It is emphasized that the total sample size of scientific Events is so small that the subclass distributions shown above must be recognized as being only roughly indicative of the actual situation. The only conclusion that can be drawn with a reasonable degree of confidence, therefore, is that most research in science whose results were found to have been used in weapon systems was undertaken as part of an organized program. Specifically, most utilized new scientific information came from organized research programs undertaken in response to recognized Defense problems.

4.3.3 Finding: *As a rule, the most useful role of science has been that of providing phenomenological explanations to the engineer.*

In all the systems studied, there were only two cases where recent research in science suggested to the engineering community a generically or fundamentally different way of reaching an objective. Those cases involved the introduction of (1) the transistor and other solid-state devices and (2) the thermal battery. The other scientific contributions were markedly similar in concept. The scientist, by gaining a reasonably thorough understanding of a process, technique or phenomenon used by an

engineer, provides the means for its greater exploitation through an explanation of the underlying scientific mechanisms.

In a sense, this "mop up" role of research in science describes 69 percent of the scientifically oriented Events. In no case was the research in science directed toward the solution of a specific problem for a particular system. Invariably the scientist looked at general problems. For instance, an investigation of the signal and noise characteristics of outgoing and returning radar pulses led to the establishment of filter theory, and the engineer, applying that theory, developed a greatly improved radar.

This example also helps define the difference alleged in the immediately preceding paragraphs. The fundamental capability of detecting or locating a target with radio energy was not a consequence of recent research in science. The scientist, observing the radar set in action, devised a means of improving its performance, and in this regard science followed technology. Within this definition, 69 percent of the research in science studied by Project HINDSIGHT served to provide useful phenomenological explanations to the engineer.

4.3.4 <u>Finding</u>: *The engineer appears to rely heavily on unified scientific theory and tabulated scientific information published in engineering-data handbooks and text references.*

Because there was a paucity of Events specifically oriented toward science, yet it was recognized that many of the technologically oriented Events showed contributions from science, a deliberate attempt was made to reconcile this apparent discrepancy through a sampling analysis. The results of this effort are best described by the following statement: The average performer of the XD Event demonstrated a high level of understanding of, and general familiarity with, unified theory.

The initial observation was that the engineer usually relies upon such scientific knowledge as Maxwell's equations, Ohm's law, the Nyquist stability criterion, Boyle's laws of gas dynamics, and Newton's laws. It would appear that the engineer remembers and uses algebraic expressions, general solutions to differential equations, or simple graphical techniques that he encountered in college, but does not seem concerned with the details of the underlying theory.

Thus it is the form in which scientific knowledge is made available to the engineer, rather than other characteristics such as the age of the knowledge, that is important. A similar conclusion regarding the most useful form of scientific knowledge is drawn from an observation that the engineer uses, as typical text references, the results of scientific or technological research that have been condensed and presented in easily handled tabular or graphical form.

To illustrate: In the development of the field enhanced, low-density transmission, secondary emission films used in the SEC vidicon (Event 05/1), G. W. Goetze, of Westinghouse, relied heavily on Bruining's handbook, *[illegible]*, which summarized what was known about secondary emission in transmission, starting with the work of Leonard in 1900 and terminating with that of S. Wecker in 1941—despite the fact that Goetze himself was identified for later work in this area (between 1964 and 1966).

Similarly, the designers of the strip-line-configured components of the transmitter and frequency synthesizer subsystems of the AN/SPS-48 radar credit the *Handbook of Tri-plate Microwave Components*, published in 1956, as having been one of their principal technical-information sources. This handbook brings together, in a form useful to the engineer, the state of the art of fabrication techniques involving selection of dielectric and metallic materials, bonding of metals to dielectrics, photoetching techniques and packaging of component assemblies. Among the designs suggested are transformers, wave-guide and coaxial transitions, terminations, attenuators, variable timers, detector mounts, power diodes, hybrid rings, directional couplers, filters and antennas. In brief, this designer's guide offers basic techniques and practical approaches to the design, fabrication, measurement and assembly of the most advanced strip-line devices for microwave transmission.

Such observations suggest that more new scientific findings would be used in weapon systems if research managers were more concerned about the form in which the new information is made available to engineers.

4.3.5 <u>Finding</u>: *Most utilized new technological information was generated in the process of solving problems identified in advanced or engineering development of weapon systems or in advancing the state of the art of generic technologies commonly associated with broad classes of weapon systems.*

Motivation of the performers of research in technology can be classified in three broad categories:

(1) The objective was a requirement of a specific system or end-item device;

(2) The objective was to satisfy a recognized generic technological requirement; or

(3) There was no identifiable objective other than the desire to forward the state of the art.

Events falling into the first category are readily discernible. Far greater difficulty was usually encountered in separating the second and third categories. Judgments were necessary concerning what authority could "recognize" a requirement, how to define a "generic" requirement,

and what measure differentiates "desired" from "required." It is suspected that this dilemma confronts every manager of a technological research program. Some insight into a partial solution to the problem is offered in finding 4.3.7.

Of all RXD Events, 61 percent had a specific system requirement as an objective. The 61 percent divided into (a) 20 percent that had as an objective a requirement established by one of the weapon systems studied in Project HINDSIGHT and (b) 41 percent that were intended to satisfy a requirement in some other system or application.

Clearly, in 27 percent of the RXD Events, the identified objective of the research effort was the satisfaction of a generic technological requirement. In a few cases, particularly when the Event involved a materials or a fabrication process, the results of the research were found to have been applied to materials or applications other than those considered by the research performer. For example, the vacuum-arc-smelting techniques developed for titanium and uranium were applied almost directly to steel production, and the plasma-deposit techniques developed for metal plating found use in the depositing of refractory materials. The number of identified examples exhibiting this transfer characteristic, however, was not big enough to warrant a statistical breakout.

In the remaining 12 percent of RXD Events, the motivation was:

(1) a commercial end item,
(2) basic research or
(3) indeterminate (usually for the reason described above).

4.3.6 <u>Finding</u>: *The program of research in technology oriented toward specific types of equipment has been a particularly successful approach to generating utilized knowledge.*

This finding examines a noteworthy portion of finding 4.3.5. Certain projects or programs supported by the Military Departments were repeatedly credited with having been the source of scientific or technological knowledge used in other weapon systems. Principal among these were the Army's Missile A and Missile B programs, the Navy's long-range mine and RETORC (research torpedo configuration) programs, and the Air Force's NAVAHO missile program.

The common characteristics of each of these included the specificity of the program's operational goals and the freedom granted to performers to explore multiple approaches to the solution of problems identified throughout the program. With the exception of the NAVAHO program, none was intended to deliver a particular operational system at a given time. In every case management was centralized, and apparently was able to maintain a practical degree of balance among the diverse scientific disciplines and areas of technology in which further work was necessary.

A general conclusion to be drawn from the two preceding findings is that weapon systems present unique demands upon the total technological potential—unique in the sense that they cannot be satisfied by the technology developed for commercial purposes. This conclusion explains the success of the aforementioned programs.

Where the application of science or technology is limited, greater specificity in defining objectives is essential. Within the current capabilities of planning methods, this appears to be most readily accomplished through quantitative description of known "real-world" problems. Actually, as well as in concept, the user of weapon systems must establish a dialog with the scientific and technological communities in which agreement is sought concerning the minimum operational capability that would be worth buying for a given price and the maximum operational capability that can be afforded at the price with forecast technology.

When agreement is reached—and here the discussion is limited to systems that are well beyond the contemporary state of the art—a deliberately advanced development program may be undertaken. Detailed designs of several potential solutions to the overall system problem can be prepared. The designs then provide the focus for a supporting research program. As long as the operational objectives agreed upon at the outset are not compromised, the scientist and technologist can have the freedom of design flexibility to allow other technological compromises. Alternative approaches to original design are essential in order to minimize risk and, at this state of the R&D cycle, are relatively inexpensive. "Metal bending," or the commitment to hardware, is essential only to the extent that interface problems can be highlighted and identified.

The value of focused program planning in science and technology is most strongly supported by examination of the NAVAHO program. Contemporary guidance and propulsion technologies, to name just two, were completely inadequate to provide the first-phase NAVAHO missile, which had a minimum range of 300 nautical miles. Although inertial, radio-inertial, radio and celestial-inertial guidance techniques held promise, no approach guaranteed success. Further, the different guidance approaches placed dissimilar requirements on the missile's flight profile—anywhere from essentially constant-altitude aerodynamic to fully ballistic—which in turn established requirements for considerably different rocket or jet engines, none of which were within the state of the art. In a similar vein, dependently variable requirements were established for other parts of the airframe and ground support equipment.

The Air Force approach to this interplay of requirements was to provide specific but very generous scientific and technological objectives, and the relevancy of the science and technology generated by the NAVAHO program to other Defense problems is fully attested to by the widespread use of the new knowledge.

The story of the Army's Missile A and Missile B programs is quite similar. The results were manifested in at least the LANCE missile system and very likely in other systems not yet studied by Project HINDSIGHT. Another advantage of a type-equipment-oriented management is demonstrated in Figure 4, the chronology of Events leading to the Mark 56 and 57 mines. Clearly the technology was developed in an orderly fashion, essentially all the requisite knowledge being available before it was needed in the end item.

Another indicator of the value of focused program planning in science and technology is provided through analyzing the rate of knowledge accretion. For this purpose the studied systems were divided into two classes:

(1) Those that went through a relatively extended preprototype and prototype development path—or, at least, for which a system-concept approach was adopted in the formulation of research and exploratory-development programs; and

(2) Those that were developed in an essentially one-step process, from technology base to final system configuration.

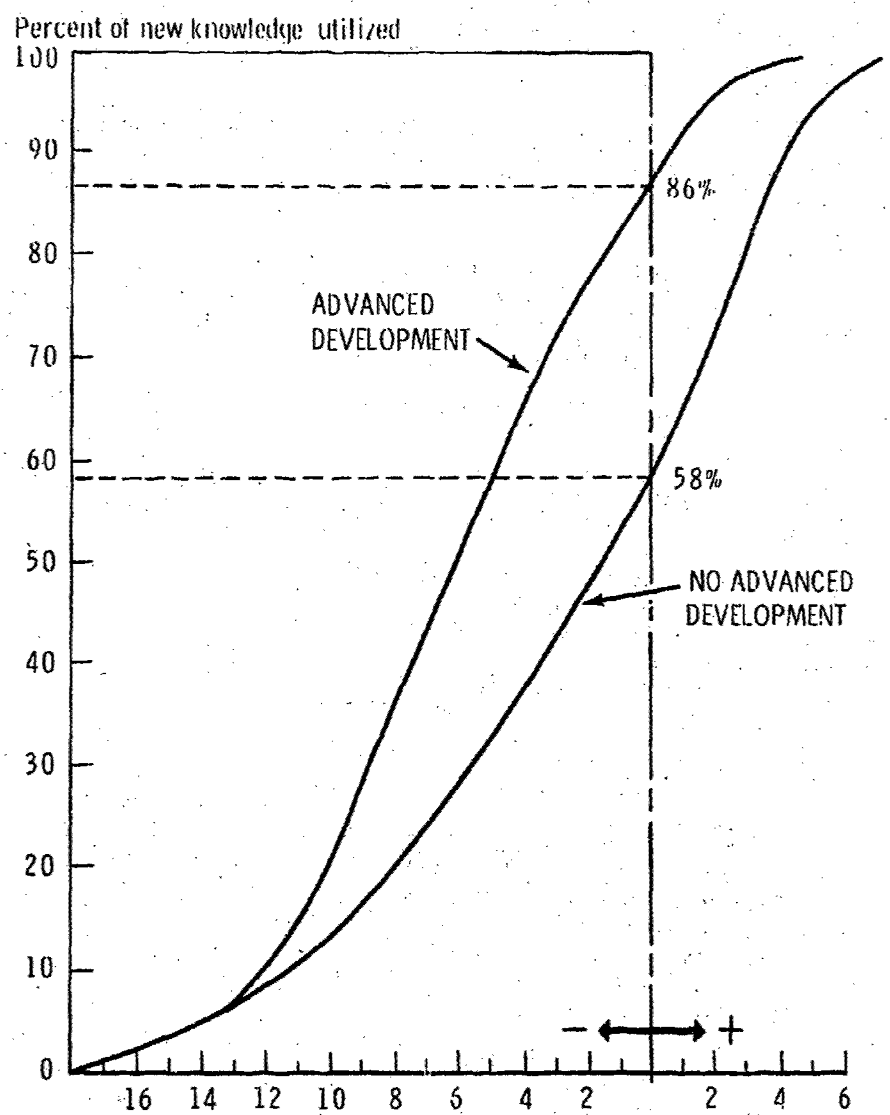
Typical examples are the Mark 56 and 57 mines (Figure 4) for the first and the LANCE missile system (Figure 3) for the second.

All RXD Events associated with each system within the two classes were analyzed to determine when they had occurred, in terms of how long before or after the system's engineering development began. The resulting data were displayed as in Figure 13. The potential advantage of using an end-item-oriented, systems-analysis approach in formulating long-range programs of science and technology is clearly seen.

The title of Figure 13, "Technical Confidence Level," was chosen to point up another advantage of focused planning. The RXD Event is generally associated with a scientific or technical problem (see finding 4.3.2). Thus Figure 13 suggests that there are typically three times as many unsolved problems at the start of engineering development when the preceding research programs in science and technology had not been the subject of focused planning. If it is assumed that the probability of finding timely, acceptable solutions to these problems follows a Gaussian distribution, the relative technical risk is not 3:1 but the Naperian antilogarithm of 3, that is, 20:1.

In retrospect, some reasons the weapon-system approach to research planning should be profitable are obvious. Coupling the research and applications-engineering communities is the natural consequence of the process rather than an afterthought. By being responsive to the identified needs of the applications engineer, the research community's interests are focused in common with those of the marketplace for research products.

## Figure 13. TECHNICAL CONFIDENCE LEVEL



(Time before or after date of decision on engineering development)

4.3.7 Finding: [illegible]

In more than 85 percent of the Technological Events, the individuals responsible for the accomplishment credit a particular applications-engineering group with having originally described the problem. The descriptions of the remaining 15 percent of those Events lack definitive information regarding the problem's source. The nature and adequacy of the communication path are self-evident.

With respect to the dilemma of the manager of a technological research program who must decide whether or not a given project should be undertaken as generic research (finding 4.3.5), it appears that some help is offered by the finding that there is a very high correlation between utilization of research results and the fact that the user had first stated the problem. Certainly it suggests that the useful authority for defining a requirement is, in most cases, the applications engineer.

Although applications engineers suggested the problem toward which research was directed in over 85 percent of the Events in technology, the technical initiative in proffering the solution in 72 percent of those Events came from the group performing the research. In the remaining 28 percent, technical initiative resided in the applications-engineering group or was shared by both groups—or the information was not available. The dominance of the cases in which technical initiative was taken by the performing group is so overwhelming and the data concerning the remaining cases are so indefinite that further resolution appears to be pointless. The characteristics of the performers are considered in section 5.

During the pilot studies preceding those of Project HINDSIGHT, it was noted that successful performers—in the sense that they achieved utilized results—were equally successful in quickly obtaining necessary funds and other capital resources. Because this quick funding appeared to be atypical of DoD research support, it was suspected that the observation was significant; consequently, a deliberate effort was made during the Task I studies to gain quantitative information on funding delays. The results of this effort were not satisfactory. In very few cases was there such a delay in funding that the performers remembered and mentioned it—or this may be the consequence of a selective recall difficulty.

The Task II study personnel are continuing to examine this matter. Subject to what would now constitute a surprising finding by the Task II team, it should be concluded that, to achieve a high research payoff, timely accessibility of capital resources is equal in importance to the recognition of a need and the existence of a source of ideas, together with the communication coupling between idea generators and users.

4.3.8 Finding: [illegible]

Finding 4.3.7 disclosed that the research-utilization factor was high when the applications engineer established the research objectives for the performing group. This implies the concomitant existence of good communications between the two groups. Available data do not describe the relative frequency with which any of the several possible communications links are used for indicating requirements. But the data do present a pattern with regard to communications in the opposite direction, that is, the passing of research results toward the eventual user.

Table VI shows the findings in terms of the several classes of research or exploratory development previously described, and considers three general classes of communications links: the informal person-to-person contact, the published scientific or technical report, and the professional seminar or symposium.

Table VI. MODES OF IDEA TRANSFER

| RXD category | Personal contact (%) | Publication or report (%) | Seminar or symposium (%) |
|---|---|---|---|
| Research (R) | 45 | 53 | 2 |
| Exploratory development: | | | |
| XD | 64 | 33 | 3 |
| XD (design) | 79 | 21 | 0 |
| XD (mfg.) | 77 | 23 | 0 |

Note: Figures are percentiles of the research class (horizontal rows).

Despite the fact that the professional meeting embodies some of the characteristics of both the other links—generally a published technical report is presented, and there is at least an opportunity for person-to-person interaction—it is seen to be the least often cited. Publication is clearly the dominant mode for the transfer of scientific information, with a transition toward informal, person-to-person communication as the specificity of the technological information increases.

It should be noted that the data presented in Table VI consider only one attribute of the seminar or symposium. The true worth of these meetings is not measured, principally because we cannot establish how many valuable personal contacts resulted from encounters at such meetings.

Gilmore, Gould and others studied the flow channels of technical information utilized in commercial firms. The results they have reported corroborate several of the findings of Project HINDSIGHT.[h]

[h]John S. Gilmore, William S. Gould, *et al.*, *The Channels of Technology Acquisition in Commercial Firms and the NASA Dissemination Program* (Denver, Colorado: Denver Research Institute, NASA CR-790, June 1967).

With regard to the large technical meetings, they state:

> Conventions, conferences, symposia, and trade shows were highly ranked channels *not so much for their formal presentation of papers* as for the opportunity to meet and exchange information with colleagues and to inspect new product displays. Many individuals questioned indicated that formal papers presented at meetings tended mainly to serve the interests of the speaker (by boosting his status), and that *they typically failed to include proprietary or really useful information.*[5] [Italics added.]

The Denver Research Institute group further reports that:

> Textbooks and handbooks tend to be from two to five years *or more* behind the state-of-the-art. Nevertheless, they were one of the most important sources of information for problem solving.[6] [Italics added.]

The words, "or more," are emphasized here because, during the HINDSIGHT information-collecting phase, it was repeatedly observed that a substantial number of the most frequently used text references were 15 or more years old.

4.3.9 Finding: *The evidence denies the commonly accepted hypothesis that relatively few organizations provide the majority of the utilized new science and technology.*

An analysis of the distribution of RXD Events and their rate of production according to performing organization reveals two principal features: Over half the identified participating organizations produced only one RXD Event, and over 70 percent contributed less than three. In the low-rate mode, the industrial laboratory was predominant, and as the rate of Event production increases the principal organizational contributor shifts steadily to the in-house DoD laboratory.

Table VII illustrates the process and shows that, when RXD Events per organization reach four or more, the DoD laboratory becomes a dominant source.

These findings are entirely commensurate with those cited earlier regarding the significant modes of information transfer, and they illustrate the obvious conclusion that it is easier to communicate technological requirements within a single organization, the DoD laboratory responsible for the system development, than to disseminate the requirements throughout a widely scattered industrial community.

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[5] *Ibid.*, p. 25.

[6] *Ibid.*, p. 26.

Table VII. RATE OF RXD EVENT PRODUCTION, BY ORGANIZATIONAL TYPE

| Number of Events | In house DoD Laboratory ( ) | Industrial Laboratory ( ) | Universities* ( ) |
|---|---|---|---|
| One | 25 | 64 | 11 |
| Two or more | 31 | 56 | 13 |
| Four or more | 36 | 52 | 12 |
| Six or more | 50 | 29 | 21 |
| Eight or more | 45 | 36 | 19 |
| Ten or more | 60 | 20 | 20 |

Notes: Figures are percentiles of the rate class (horizontal rows).
*Includes science and technology centers.

4.4 <u>Fourth Strategy</u>: If the findings of the first strategy indicate a significant reliance on new science or technology, devise a value-cost index (or set of indices) which offers a quantitative measure of the return on investment in research, in terms of the enhanced cost-effectiveness of the weapon systems made possible by the purchased knowledge.

The findings relevant to this strategy clearly demonstrate the reliance of new weapon systems upon the results of research in science or technology to achieve an improved cost-effectiveness ratio. Section 7 of this report, "Requisite Level of Investment in Research," gives some gross estimates of the relationship between the cost of research and the value received; but a more useful, precise, quantitative indicator for describing the effectiveness of investment in research has not yet been devised.

The studies made thus far offer some insight into the factors to be considered in an equation relating cost and value. The effort to devise the cost-value index (or indices) should continue.

4.4.1 <u>Finding</u>: *Multiple uses of scientific and technological advances within a multiplicity of weapon systems require either that the research investment cost be apportioned among all utilizing systems or that a portion of the total value added by each utilizing system be attributed to the identified Event.*

A given RXD Event may manifest itself one or more times in a single weapon system, and it may contribute to an increased cost-effectiveness ratio in one or more systems. Considering only the 20 systems that provide the data basis of this report, at least 20 percent of the 710 Events were identified through more than one system. During the course of the investigations it was frequently learned that the knowledge accruing from an Event had been used in systems other than the 20 under study. In fact, it is believed that, at the time of the study, over 80 percent of the RXD Events had contributed to three or more applications aside from those in the study.

4.4.2 Finding: [illegible]

This finding was discussed previously because of its relevance to the first strategy (section 4.1), which involved determining the extent to which new science or technology was required. A scientific or technological advance has no inherent value other than its utilization. Realized value, therefore, is contingent not only upon the decisions to develop and procure each type of weapon system that could benefit from the new knowledge, but upon the absolute cost effectiveness ratio of the new systems and their predecessors. This suggests that the relationship between cost and achieved operational capability is not linear and may be exponential, with requisite research costs rising much more rapidly than capability.

An empirically derived relationship between improvement, complexity of predecessor equipment, and relative cost-effectiveness of predecessor and successor is stated in section 7. The relevant curve (see Figure 19) confirms the hypothesis of exponential relationship.

4.4.3 <u>Finding</u>: *Markedly improved weapon systems result [illegible] combining a considerable number of scientific [illegible] advances.*

This finding (also discussed in relationship to the first strategy), considered with the recognized multiple use of a given Event, shows that only a gross approach (i.e., considering the total cost of all relevant research) will be meaningful. Further, if all research costs are to be included, the value-received side of the equation must take into account all weapon systems that use any part of the new science or technology. This introduces the notion that value must be computed in terms of the weapon-systems mix rather than a mean or median cost-effectiveness ratio; and the problem of assessing the cost-value relationship in research becomes a matter of operations research rather than accounting.

4.5 <u>Specific Challenges Regarding DoD Management</u>: Establish the significance of specific questions or challenges raised by critics of the DoD research programs.

The derivation of such challenges is described in the introduction to this report. In this section, pertinent findings are discussed in terms of the challenges, which again are presented in the form of hypotheses.

4.5.1 <u>First challenge:</u> The DoD's requirements for information in science and technology can be satisfied to such an extent by research supported by the National Aeronautics and Space Administration and the National Science Foundation that significant reductions can be made in the applicable portions of the Defense budget.

<u>Finding:</u> *The dominant portion of new science or technology used in weapon systems was the result of DoD-financed programs.*

Less than 2 percent of DoD-utilized research results, both scientific and technological, came from programs supported by other Federal agencies, state governments and foreign governments. This is not surprising in the light of the finding that 61 percent of the RXD Events occurred as the result of a specific technological weapon-system requirement, and that 27 percent were the result of research conducted to satisfy recognized generic technological requirements of broad classes of weapon systems. Of the remaining 12 percent of Events, 9 percent were the result of scientific research, most of which was oriented toward Defense problems; and 3 percent were for the solution of commercial problems.

Relatively little undirected research (as defined in Table III) is in fact sponsored by the DoD. The larger part was found to be very relevant to mission and therefore likely to be of primary value to users having quite similar requirements.

During 1946, the starting point of the period studied by Project HINDSIGHT, the Military Departments invested about $115 million in the categories considered here as RXD. At that time the investment by other Federal departments was negligible. As noted in Appendix F, military spending increased steadily and gradually to $1.5 billion in 1963. Comparatively significant funding in these areas by other Federal departments or by industry did not appear until late in the 1950s. Their expenditure rates increased more rapidly than the DoD's, so that by 1963 the other Federal agencies were spending about $6.3 billion on scientific and technical investigations, and industry, about $2.1 billion. As a result, for the entire period from 1945 to 1963, the DoD spent altogether about $10 billion; non-Defense expenditures for those years totaled $6 billion.

If the process of technological growth were truly random—that is, independent of users' requirements—Project HINDSIGHT should have found that a much higher percentage of RXD Events were funded by non-Defense organizations. Because of differences in starting time and growth rate of the two funding categories, a ratio of 60 to 40 percent would not be likely, but it would be closer than the observed 94 to 6 percent.

This discussion and the ratios suggested relate to all funding sources other than DoD, rather than to the other Federal agencies alone.

While it is a departure from the true intent of the hypothesis, the discussion provides a better (and still intellectually consistent) basis for analysis. It demonstrates that the words science and technology are convenient artifices. In fact, it would be more realistic to speak of the many sciences and technologies. The particular field of science or technology that is important to any user need bear no similarity to that of another user, but society for convenience has adopted those words as generic terms to signify the many sciences and technologies thus categorized.

Thus, although both Defense and NASA may be said to conduct scientific and technical investigations in an area termed rocket propulsion, for example, it cannot be concluded that their work is duplicative or even usefully complementary. One might suspect that, as long as NASA is interested in cislunar exploration, the related equipment and propulsion technologies will be quite similar to those associated with the DoD's satellite and ICBM systems. Clearly, however, there will be a technological divergence where NASA's interest extends beyond the cislunar into regions in which magnetohydrodynamic and ion propulsion systems are practical. Similar trends can be expected in communications and perhaps in materials, only generic names remaining in common.

The conclusion is that even greatly increased expenditures for scientific and technical investigations by Federal agencies other than the DoD are unlikely to result in satisfying many Defense needs.

4.5.2 <u>Second challenge:</u> The currently high-level support of basic work is producing scientific and technological information at such a rate that it cannot be effectively digested, interpreted, disseminated or put to practical use.

<u>Finding</u>: *The available information is being adequately broadcast but is insufficient, despite the level of expenditures, to satisfy all requirements.*

Were this allegation true to any significant extent, there would be a very low probability that the result of any given research effort would have many uses in different weapon systems. In fact, over 80 percent of the RXD Events are believed to have contributed to three or more different weapon systems, and those systems generally were developed by different engineering teams.

Figure 14 summarizes the time distribution of the utilized RXD Events shown in Figures 1 through 11. The data have been normalized to the dates of system design, engineering development, or first production contract. Approximately 33 percent of the requisite new scientific and technological information is seen to have been generated after the normalizing date, and to a considerable degree was paid for with engineering-development money.

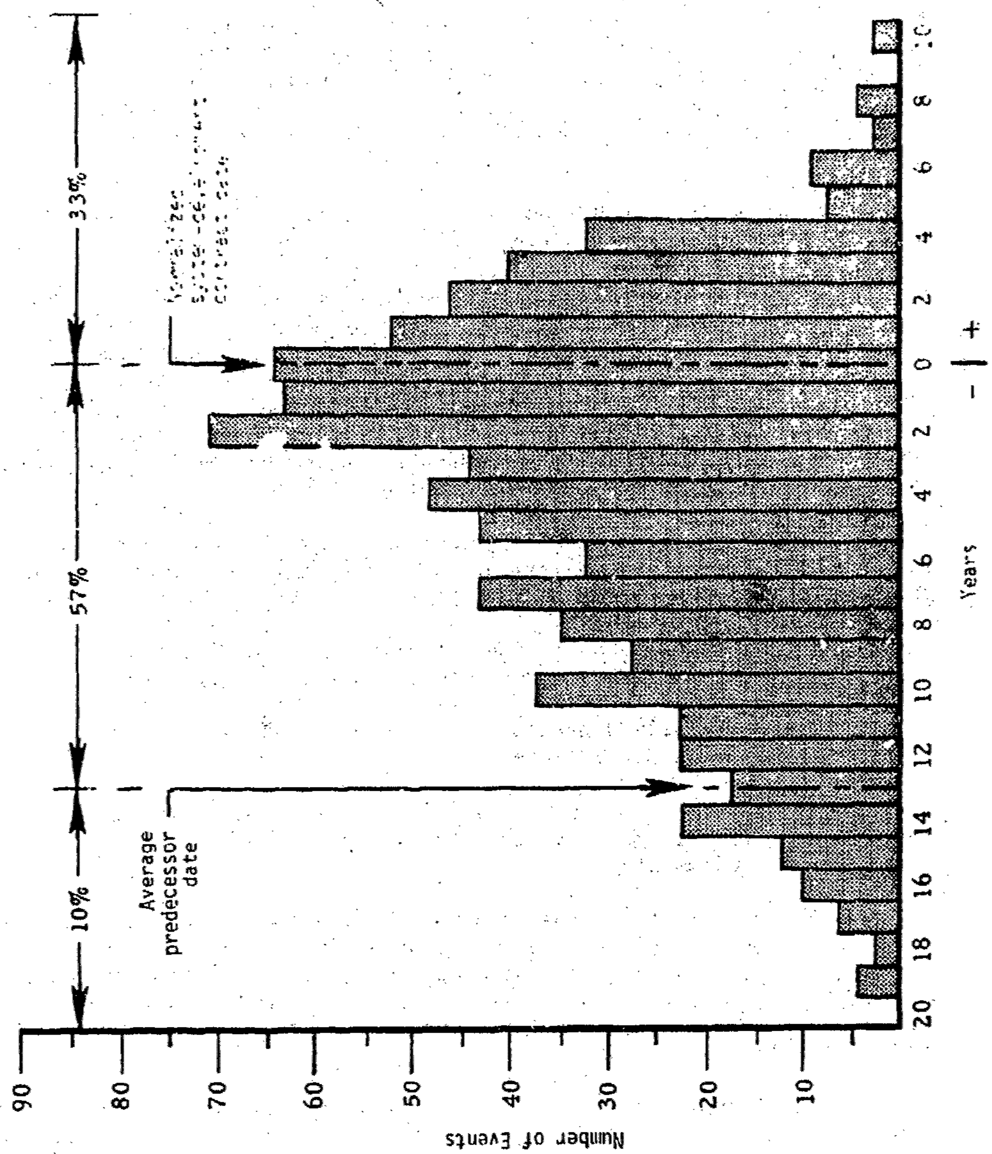


Figure 14. Time Distribution of Utilized RXD Events

Not only [illegible] the generation of technology currently insufficient for present requirements, but the amount of new scientific and technological knowledge required for an incremental improvement in operational capability is found to increase with the complexity of the weapon system, which suggests that a constant budget for the military sciences could result in an increasing deficiency in knowledge as time passes.

> 4.5.3 <u>Third challenge</u>: Department of Defense management of research in science and technology, in order to be fully effective, must make comparative cost-effectiveness analyses for each separately identifiable research effort.

4.5.3.1 <u>Finding</u>: [illegible]

In this challenge, the effectiveness of the management exercised by the DoD over the military-sciences budget category is questioned, viz.:

> Improved management and critical selection procedures such as those which are being applied to complex and costly weapon systems could well and profitably be extended to the supporting efforts included in the "Military Sciences" category.

Generally, the synergistic consequence of hundreds of identifiable advances is the basis for a markedly superior weapon system, rather than one, two or three important scientific or technological contributions.

In order to apply a cost-effectiveness approach, it would be necessary to describe fully each combination of advances that could permit a future system, and then compare the combinations. The task would be further complicated by the multiple-use potential of the individual research effort. The "shopping lists" for all considered weapon systems would have to be compared before the most "cost-effective" research program could be determined. It is suspected that the expense of such a procedure would exceed the anticipated savings, while the time required would cause irreparable damage to the program.

A possible alternative approach would be the development of analytical procedures to aid in allocating resources among specific technologies that are important to Defense. The feasibility of such an approach is suggested by the finding that certain technologies appear to be unique to the DoD. It is reasonable to expect that the military services could identify and rate their future required operational capabilities, that those capabilities could be reexpressed in terms of future desired military equipments, and that scientific and technological advances to enable developing those equipments could be identified. Then, it should be possible to introduce economic marginal-return analyses to assist in decisions on resource allocation.

Designing such a procedure appears to be within the current state of the management art. Its implementation would be generally consistent with the Project HINDSIGHT findings in regard to the selection of research tasks.

Undoubtedly, in an activity as large as the DoD's research program, there are some marginal tasks. At best, the suggested management approach could eliminate some of them, at the same time introducing a risk suggested by the following finding.

4.5.3.2 Finding: *A significant number of very important scientific contributions came from sources other than contemporarily recognized experts.*

The investigation of a sampling of the RXD Events discloses a fairly common pattern. Both the producers of the utilized scientific effort and their contemporary peers were aware of the avenues of exploration that the others were taking. The disagreement by contemporary authority as to the merit of the approach that eventually found use was so marked that the successful performer broke with his peer group and secured new funding. More than anything else, these examples point out the necessity for ensuring competition within bureaucracy and the absolute essentiality of maintaining decentralized funding authority, or a multiplicity of funding sources, for every scientific discipline and area of technology. The challenge suggests a diametrically opposed move.

As a result of decentralized planning throughout the time frame considered by Project HINDSIGHT, 67 percent of the requisite new knowledge was available before it was needed. Since it is recognized that the saving to the nation as a consequence of this new knowledge exceeds by orders of magnitude the total cost of the research program (see section 7), the real measure of the effectiveness of research management is the degree to which new knowledge is available when needed.

4.5.4 Fourth challenge: Significant portions of the Defense research program may be operating at or near a point of marginal returns.

The analysis presented in this report is based in 710 RXD Events identified by studying 20 weapon systems. It is estimated that a more exhaustive study of only those systems would have revealed an additional 400 to 1000 Events. The median cost of an RXD Event was $45,000. An average additional cost factor of 15 was found necessary to carry the median Event from initial demonstration of feasibility to readiness for application.

Recognizing the weakness of these figures for anything more than order-of-magnitude estimates, and assuming that there were only 1000 Events in all, one can place the cost of the RXD Events for these 20 systems at approximately $600 million out of the estimated total of $10 billion invested by the DoD in research between 1945 and 1963. The

resulting weapon systems have successfully stood the test of cost effectiveness. *Clearly the military defense program is not operating at a [illegible] submarginal manner. Whether or not significant portions are, is a matter of subjective judgment.*

If the resource-allocation procedure suggested in the discussion of finding 4.5.3.1 were to be developed and implemented, submarginal research tasks could be identified in a somewhat less subjective fashion.

4.5.5 Fifth challenge: The support of scientific research in the universities, by the DoD and at current funding levels, significantly affects the availability of the best faculty talent to teach students.

Obviously, any activity undertaken by a professor other than teaching or counseling the student body could detract from his primary work simply by reducing the time available for it. But it is generally agreed that the professor must continue to do—or to direct—research in his chosen area or risk having his scientific expertise rapidly diminish. Thus the real concern (and this may be inferred from the challenge) is whether or not DoD-supported research activities at a university have, in the balance, a deleterious effect on the students.

The investigations under Project HINDSIGHT do not provide a direct and unequivocal answer to this challenge. But many of the findings, reinforced by conclusions of other relevant studies,[7] offer useful insight. Findings of this Project that bear on this matter (developed more fully in section 5.3) are summarized here:

Most important, the HINDSIGHT data show that the universities receiving the greatest amount of DoD funds for research graduate a disproportionately high percentage of the people who later produce the science and technology used by the Departmentof Defense. Specifically, the 23 universities responsible for doing most of the research that the DoD supports in academic institutions award only 25 percent of the doctorates earned in the United States, but that group includes 50 percent of the Ph.D.'s who have been identified as important contributors to RXD Events. Similarly, the 23 universities most heavily supported in research by the DoD award about 11 percent of the Master's degrees in science and the arts in the nation, but 46 percent of the identified contributors received their degrees at these schools.

The findings of Marquis, Allen and de Solla Price,[8] based on their studies of the postgraduate education of the country's engineers, are

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[7] D. G. Marquis and T. J. Allen, *American Psychologist*, 21, 1052, 1966. Derek J. de Solla Price, "Is Technology Historically Independent of Science? A Study in Statistical Historiography," *Technology and Culture*, [illegible], 4, Fall 1965, pp. 553-568.

[8] *Ibid.*

thoroughly consistent with the foregoing observations, and clearly suggest that the engineer continues through life armed primarily with the science he learned as an undergraduate student. The greater his professors' knowledge of the state of the art, the more advanced was his scientific education. So it is not surprising to find a possitive correlation between the level of the DoD's support of a university's research and the subsequent useful productivity of its graduates.

The time elapsing between an engineers' graduation and the peak of his productive work—on the average, about 10 to 15 years—seems to be independent of his scholastic experience. All the patterns revealed in this study suggest that it is a function of the rate of the individual's contact with actual working problems. At this distance from his last significant exposure to science, the engineer has learned enough about typical problems and their technical solution that he can solve a new technical problem on the basis of that experience and his knowledge of science.

**In brief:** *All observable quantitative measures deny that there is any great substance to the challenge that DoD-supported research in universities has a generally harmful effect on the students at those institutions.*

# 5. ADDITIONAL FINDINGS

The primary data base of Project HINDSIGHT consists of 710 discrete Event descriptions in the prescribed format (see Appendix C) and 511 detailed biographical sketches of the performers involved. Of the Event descriptions, 684 are complete in all essential details; 26 are adequate to support only a portion of the analyses. The findings presented in section 4 are those considered most relevant to the questions outlined in sections 1 and 2 of this report, but the analyses on which they were based did not exhaust the potentials of the accumulated data.

In this section and the next two, this information is considered further. First, the data are displayed, and where possible correlated with the findings of other reported researches, and some inferences are drawn. Sections 6 and 7 contain additional inferences regarding the nature of a high-payoff research environment and future Defense requirements for research funds.

## 5.1 Quality of the Data

5.1.1 Uniformity: Despite efforts to maintain uniformity in the data base, there is a considerable amount of unevenness in the more subjective areas. Problems arose, for example, in separating the really inventive activities that advanced science and technology from more routine engineering work barely within the state of the art. Consensus of the study teams was the primary criterion for screening the activities in this respect. A review by the Project Director followed, resulting in the rejection of 2 to 3 percent of the Events surviving the first scrutiny. Undoubtedly, another independent review would have somewhat different results.

Also contributing to the data's lack of uniformity was the difficulty met in ascertaining the precise terminal point of an Event. By definition, an Event terminated at the instant feasibility was first demonstrated or validity proved. In practice, judgments about what constituted proof of validity differed widely. Because this problem was never satisfactorily resolved, the distributions of Event duration and cost were viewed in the data analysis as only generally indicative of the situation.

5.1.2 Nature of the Events: Although each Event was considered unique, a preliminary analysis suggested that it would be possible to classify most of the Events by type with a relatively limited set of descriptors. To this end, 15 descriptors were selected; and for each Event it was stated, "This Event advanced the state of the art by the application of ______ to ______ for ______," employing the three appropriate descriptors from the following list.

DESCRIPTORS FOR CLASSIFYING EVENTS

| | |
|---|---|
| Research | New function |
| Mathematics | Established function |
| Natural phenomena | Manufacturing (process) |
| Specific function | Equipment |
| New technique | Analysis |
| Established technique | Design specification |
| New material | Theoretical validation |
| Established material | |

The consequent distributions were analyzed, with the following indications:

5.1.2.1 <u>Scientific Events</u>: *About 9 percent of the Events involved discoveries or advances arising from scientific investigations.*

It should be noted here that a very rigorous definition of "science" is used in this report (see Table II). For example, it is not synonymous with the DoD budget category "research," although there is a useful degree of similarity. In interpreting the significance of the 9-percent figure, however, it is more important to know that, even though the Event occurred in a university and the performers might normally be called scientists, if the nature of the work tended more toward technology than science the Event was categorized as technological. This particular finding, therefore, says nothing about the relative value of scientists vs. engineers or of an organization's science and engineering departments.

Recently the Department of Defense budget for research has been roughly one-third the size of the one for exploratory development. If there is any relationship between a program's size and the number of utilized results, the 9- to 91-percent ratio of scientific to technological Events—rather than the logical 1:3 ratio—suggests that, in practice, a considerable portion of the work funded by the DoD as research is in fact technology, not science.

5.1.2.2 <u>Materials</u>: *The development or application of new materials was the subject of slightly over 30 percent of the Events. Of those, about 3 percent actually resulted in the creation of a new material. The remaining 97 percent dealt with the exploitation of a new material's characteristics (a) to permit the use of a new manufacturing process (15 percent), (b) to enable the development of a new device (16 percent), or (c) to advantageously replace an older material for reasons other than manufacturing economy (38 percent).*

For example, the last category might include the replacement of germanium by silicon in solid-state devices, or the use of aluminum instead of steel in the carriage of a howitzer.

In general, this finding clearly demonstrates the importance of materials research in the advancing of technological capability. The

distributions within this 30 percent of Events, however, suggest that efforts devoted to gaining a complete understanding of all characteristics of a new material and to ensuring that this knowledge was widely distributed throughout the engineering community would be more useful than attempts merely to seek another, somehow improved material. Obviously, a commensurate recommendation would be stated in terms of relative emphasis rather than a choice of alternatives.

5.1.2.3 Functions: In determining whether the consequence of an Event was the ability to accomplish a new function, as opposed to improved ways of performing an established function, it was necessary to use definitional criteria.

In general, if an older device or technique could have been used to achieve the operational characteristics set by the engineer—even at a higher cost or with slightly less reliability—it was held that the Event merely offered better ways of executing an established function. Converselv, if the Event resulted in a higher level of capability than existed before (e.g., greater power output by a radar transmitting tube, higher specific impulse of a new propellant), the result was considered to be a new capability.

*Within these broad criteria, the invention of devices or techniques, other than through the exploitation of a new material, accounted for 33 percent of the Events. About 75 percent of these made possible a new function or offered a new capability; 25 percent offered improved ways of accomplishing an established function.* These figures suggest that, early in the engineering development of a system, about three times as much attention is paid to meeting performance specifications as is given to lowering cost or increasing the system's reliability. The data would therefore support the hypothesis that, at the time of engineering development, most advanced weapon systems are at or near the technological state of the art.

5.1.2.4 Design: *Inventions, or concepts, involving approaches to system or subsystem design were the bases for a little more than 4 percent of the Events, or an average of about 1.5 Events per system studied.*

In the opinion of the study teams, this suggests that the fundamental concepts underlying these systems and major subsystems did not differ greatly from those on which other existing military equipments of lower performance were based. The main conclusion is that markedly advanced new weapon systems emerge as a consequence of the skillful selection and integration of many innovations from diverse technologies, which combine to produce the performance demanded. It is unlikely that such weapons would come into being as the result of the mythical "great new idea."

5.1.2.5 Problem Analysis: Almost 14 percent of the Events evidence a different but not necessarily unexpected characteristic. They appear to consist of analyzing a problem in detail and coupling the results with an almost morphological survey of available technologies in order to find a useful solution. None of these Events can be described as a period of creativity followed by the test of an idea that came into being during that period. The ingenuity observed in this class of Events is revealed more particularly in the framing and analysis of the problem than in the eventual solution.

Philosophically, the activity described would seem to follow the common concept of engineering more closely than the finding 5.1.2.3) that some 33 percent were inspirational inventions. If the data had been structured somewhat differently in this portion of the report, many Events included in the discussions of scientific research (5.1.2.1) and materials (5.1.2.2) would also have consisted of analysis followed by solution. In fact, that may be a more typical description of an Event than the one chosen for the HINDSIGHT study (see Appendix B). It certainly is easier to understand the high cost of scientific and technical research when one appreciates the tremendous amount of analysis and search involved.

5.1.2.6 Other Events: Finally, 11 percent of the Events lack any obviously common characteristic, except that each involves some amount of creativity or ingenuity.

5.1.3 Content of the Events: The Events can also be usefully categorized in terms of the primary scientific or technical area involved. Since the weapon systems and equipments selected for this study are generally typical of those that are important to the DoD, it may be conjectured that a ranking of the sciences and technologies, in terms of the frequency with which Events occurred in each, would give a measure of their relative importance in, at least, the immediate past. The Field and Group Structure[9] classification code and descriptors of the Committee on Scientific and Technical Information (COSATI) were used, with the resultant distribution shown in Table VIII.

It cannot be concluded from these data that electronics is more important to a missile system than, for example, propulsion, navigation or communications. In the absence of any one of them, the final system would very likely be inadequate. Because each Event involved skilled people, however, the distribution in Table VIII suggests the relative number of scientists and technologists that would be required in each of the areas listed to maintain a balanced base of professionals.

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[9]*COSATI Subject Category List (DoD-Extended)* (Washington, D.C.: Defense Documentation Center, Defense Supply Agency, AD-624 000, December 1965). [COSATI—Committee on Scientific and Technical Information, Federal Council for Science and Technology.]

Table VIII. SCIENTIFIC AND TECHNICAL AREAS OF EVENTS: FREQUENCY OF OCCURRENCE

| Area | % |
|---|---|
| Electronics | 25.2 |
| Ordnance | 12.3 |
| Missile technology | 10.5 |
| Propulsion and fuels | 9.9 |
| Aeronautical science | 9.9 |
| Materials science | 7.7 |
| Navigation and communications | 6.4 |
| Physics | 5.3 |
| Mechanical and civil engineering | 3.2 |
| Methods and equipment | 2.1 |
| Behavioral science | 1.9 |
| Chemical technology | 1.7 |
| Mathematics | 1.5 |
| Nuclear science | 0.6 |
| Biological science | 0.6 |
| Atmospheric science | 0.4 |
| Military science | 0.4 |
| Energy conversion | 0.4 |

## 5.2 Motivation for the Events

In this study, motivation is defined in a very narrow sense. The objective here was to ascertain what recognizable influence, if any, led directly to the creative act identified as the start of an Event. Excluded were such matters as the reason the performer was in a position to do the relevant work, whether the effort was sought of his own volition, what personal drives may have contributed to his motivation, and the like. In this way, the task was considerably simplified.

5.2.1 Kinds of Motivation: The "permitted" categories of motivation were those shown in Table IX. Definitions of directed and undirected research are given in Tables III and IV. Alternatively, these categories might be more adequately described as phenomena-oriented and applications-oriented research—but only if it is clearly understood that neither orientation would exclude investigations of a basic nature. Within these definitions, the eight very important Events in the history of the transistor are classified as directed research because they all occurred at the Bell Telephone Laboratories, which is obviously applications oriented.

Table IX. DISTRIBUTION OF MOTIVATIONAL CATEGORIES

| Category of motivation | % |
|---|---|
| Science: | |
| Directed research (DoD) | 7.0 |
| Directed research (non-DoD) | 2.0 |
| Undirected research | (0.2) |
| Technology: | |
| Generic (DoD-oriented) | 27.0 ±2 |
| Advanced development or system concept | 41.0 ±2 |
| System in engineering development | 20.0 |
| Not DoD-oriented | 3.0 |

In generic technology, the attention of the performer is directed to a broad spectrum of functionally similar, general-purpose technological building blocks. Examples of this class are general-purpose transistors, ferrous and some nonferrous structural materials, liquid and solid rocket propellants, explosives, and printed-circuit boards. As the focus of the performer's attention is sharpened by the consideration of possible specific applications suggested by a particular system concept or by a system actually in preprototype development, the motivation for his efforts falls into a new category—advanced development or system concept.

There is an overlapping of generic and system-concept technology in many aspects, especially when the same people are responsible for both system design and the sponsoring of growth in the relevant technologies. For example, there are regions of technological overlap in missile guidance and radar in which it is difficult to assign an effort to either category with any degree of certainty. Further, the performer often finds it hard to unequivocably trace his motivation. Thus, from 2 to 3 percent of the Events shown as generic and system-concept technology might be shifted.

5.2.2 Other Motivational Links: In addition to determining the performer's motivation, information was sought regarding other, non-psychological factors that might have directed his attention toward the activity that culminated in an Event. In a very crude sense, the motivation was the objective that guided the performer, whereas the motivational link is the reason he was so guided.

Table X presents the distribution of Events among the eight most obvious links. The three percentage columns show the sequential participation of each link in an Event involving additional acts of creativity. Of the several categories, contractual requirement, routine area assignment, and spontaneous internal conception are self-explanatory. In the

others, the performers were informed of the existence of a need, or a possible solution for an already identified problem, by way of the indicated transfer link.

Table X. MOTIVATIONAL LINKS

| Category | Primary (%) | Secondary (%) | Tertiary (%) |
|---|---|---|---|
| Contractual requirement------ | 11.1 | 30.5 | 38.1 |
| Routine area assignment------ | 47.8 | 42.7 | 33.3 |
| Technical report------------- | 14.8 | 18.1 | 16.6 |
| Professional meeting--------- | 1.5 | 2.2 | 4.8 |
| Extraorganizational person-to-person----------- | 8.0 | 5.1 | 2.4 |
| Spontaneous internal conception---------------- | 9.5 | 0 | 0 |
| Analysis of foreign product------------------- | 0.5 | 0 | 2.4 |
| Newly hired personnel-------- | 1.6 | 1.4 | 2.4 |
| No link apparent------------- | 5.2 | 0 | 0 |

The dominance of the routine area assignment among these categories should have been anticipated in the light of other findings of this study. As noted in connection with finding 4.3.7, in 85 percent of the Events the creative activity was in response to a problem brought from outside the performing group. Where more logically should a problem be taken than to a group of professionals who are known to be regularly working in a technical area in which a solution is likely to be found? And what most probably would be the nature of a solution offered by a group that is active in certain technological areas?

In describing the production rate of RXD Events, Table VII (page 48) demonstrates that a mission-oriented establishment (the in-house laboratory), if at all involved in an Event, tends to be deeply involved. Apparently, having developed expertise in areas pertinent to its mission, the laboratory is brought relevant problems by outside organizations that recognize this expertise.

These findings form a consistent pattern and consequently offer some guidance to management. They suggest that usable ideas are more likely to be produced if an organization deliberately establishes a reputation for skill in a limited number of problem-associated technologies, instead of diversifying its talents over a wide range of technical fields.

## 5.3 Funding of Events

Information was gathered with regard to two aspects of Event funding: (1) Who furnished the money? (2) Approximately how much money was involved? An Event was restricted by definition to the "initial demonstration of validity or feasibility" in the hope of keeping the number of funding sources to a manageable minimum, but even so multiple funding was found to be a common occurrence. In fact, 20 percent of the Events had at least two simultaneous or consecutive sponsors, and 6 percent had at least three. Dual funding by consecutive sources appears to have resulted from one or more of several situations:

(1) The idea occurs in an organization that is unwilling to fund more than the most superficial test;

(2) The idea occurs in an organization that lacks the technical ability to accomplish the requisite tests; or

(3) The idea occurs in, and is tested by, one organization, but a second organization which is unwilling to accept those test results funds a more detailed project.

The simultaneous funding by multiple sources invariably happened when two or more organizations were interested in pursuing an idea and agreed to share expenses or talent, or both.

Table XI shows the frequency with which the several identified funding sources appeared.

Table XI. FUNDING DISTRIBUTION FREQUENCY

| Source | Primary | Secondary | Tertiary |
|---|---|---|---|
| Department of Defense | 574 | 131 | 37 |
| Defense-oriented industry: | | | |
| Specified industrial R&D | 18 | 1 | 0 |
| Specified profits from other DoD contract | 3 | 0 | 0 |
| Unspecified | 51 | 2 | 0 |
| Non-defense industry | 35 | 4 | 2 |
| Non-DoD Federal | 8 | 0 | 0 |
| Foreign and miscellaneous | 9 | 0 | 0 |

Table XII reduces these data to participation percentages on the basis of number of Events rather than funding level.

Table XII. INCIDENCE OF EVENT FUNDING

| Funding source | |
|---|---|
| Department of Defense | 84.8 |
| Defense-oriented industry | 8.6 |
| Other industry | 4.6 |
| Other Federal | 1.0 |
| Foreign and miscellaneous | 1.0 |

Each of the 28 Events in which there was simultaneous multiple funding involved the DoD as one contributor and defense-oriented industry as the other. Distribution of consecutive funding participation by sponsor may be inferred from Table XI. Where the initial support came from either the DoD or defense-oriented industry, the follow-up support was provided by the DoD. Where non defense industry furnished the initial support, it tended also to give the follow-up support.

The actual dollar level at which a given Event was supported varied from none (other than the performer's salary for a few days up to a week) to figures well in excess of a million dollars. The information was provided by the Event performers, who generally attempted to estimate, in terms of men, materials and overhead, a dollar equivalent that would be an approximate measure of the Event's cost. These data are considered roughly indicative of the cost of advances in science and technology.

Because these estimates concerned the approximate cost of incidents that had occurred as much as 20 years before, and because there was little uniformity in the way the many study participants applied the definition of an Event, an average Event cost is not a particularly meaningful figure. Instead, the median cost of an Event is offered as being more descriptive of the situation. Table XIII gives median cost figures for the dominant Event categories, and Table XIV displays Event cost distribution, regardless of source or other factors.

Table XIII. MEDIAN COST OF EVENTS

| Category | Median cost |
|---|---|
| Science | $60,000 |
| Technology (DoD-funded Event) | 45,000 |
| Technology (industry-funded Event) | 33,000 |

Table XIV. DISTRIBUTION OF EVENT COST

| Cost range | % |
|---|---|
| Under $10,000 | 17.7 |
| $10,000 - $50,000 | 32.6 |
| $50,000 - $100,000 | 19.0 |
| $100,000 - $250,000 | 17.0 |
| $250,000 - $500,000 | 6.3 |
| $500,000 - $1,000,000 | 3.5 |
| Over $1,000,000 | 3.9 |

### 5.4 Idea Protection

The flow of ideas, as well as their application, may be restrained by controlling the information in three ways: Assigning it a Defense security classification, labeling it proprietary, usually to industry, or subjecting it to the patent process. The incidence of these restraints among the 710 Events is shown in Table XV. Since it is possible for an idea to be patented and at the same time classified as Defense security information, the percentile figures are not additive. Nor is "Special Handling" additive, for it is a subclass of both "Secret" and "Confidential." The number of Events that are (or were) considered to be proprietary information by the performing organizations is not known.

Table XV. IDEA PROTECTION

| Restraint | % |
|---|---|
| Defense security classification: | |
| Special Handling | 2.5 |
| Secret | 4.6 |
| Confidential | 12.2 |
| Patented | 18.0 |

Recognizing that this study has identified most of the important scientific and technical advances in weaponry and other military equipments over the past two decades, and in view of the current European concern over the so-called technology gap,[10] these data are particularly enlightening. To the extent that such a gap exists, Federal security

[10]H.R. Lieberman, "Technology Gap Upsets Europe," *New York Times*, 12 March 1967.

control over the flow of information is obviously not a significant contributor. In 83 percent of the cases there was no legal constraint on open publication of the information.

The data, of course, do not measure the effect on information flow of constraints imposed by Defense contractors, either by discouraging their people who might desire to publish or placing deliberate restrictions on proprietary information.

## 5.5 Participating Organizations

In the same way that an attempt was made to curtail funding sources, the definition of an Event was deliberately framed to minimize the possibility that a number of organizations would be found to have participated in any one Event. Again, success was not complete. Only in 78 percent of the Events was all the technical work done within a single organization. In 17 percent of the cases, two organizations were identified, and in 5 percent there were three. Where multiple performing organizations were identified, the combinations included the following:

Government laboratory / Government laboratory
Government laboratory / university
Government laboratory / industry
industry / university
industry / industry

Thus it is not highly illuminating to discuss the distribution of performing organizations in terms of percent of Events by organizational class. Instead, Table XVI presents the incidence of participation in Events as a function of organization class.

Table XVI. INCIDENCE OF TECHNICAL PARTICIPATION BY CLASS OF PERFORMING ORGANIZATION

| Organization class | Incidence (%) |
|---|---|
| Government laboratory | 43.6 |
| DoD | (42.3) |
| non-DoD | ( 0.9) |
| industry-operated | ( 0.4) |
| Industrial | 44.2 |
| profit | (42.3) |
| not-for-profit | ( 1.9) |
| University | 10.6 |
| academic institution | ( 5.4) |
| research center | ( 5.2) |
| Foreign laboratory (all classes) | 1.6 |
| | 100.0 |

Since Table XVI covers the entire period from 1945 to 1963, it is not a measure of the current relative importance of these organizational classes. The trend in relative importance of the Government laboratory and industry, the two primary contributors over the whole time frame, is illustrated in Figure 12 (page 38).

Section 4.3.1 noted that about 75 percent of the university-credited RXD Events came from associated science and technology centers or arose out of recognizably mission-oriented programs (e.g., the investigations in missile base drag characteristics, Event No. 0060, under the direction of Professor Korst, University of Illinois). About half of the RXD Events that took place in academic institutions proper fell into the category of those that were recognizably mission oriented. Thus, the referenced paragraph and Table XVI are consistent.

## 5.6 Contributing Scientific and Technical Personnel

In tracing the histories of the utilized new science and technology, 1,295 people were identified as having made significant contributions to RXD Events. Detailed personnel résumés were obtained from 514, almost 40 percent of them. Analysis of those résumés provides the distributions presented in subsequent paragraphs.

Two relatively simple tests were applied to the sample as a check on its validity. In the first test, the distribution of résumés, in terms of category of employing organization, was compared with the distribution of Events that occurred within that organizational class. The results of this test are shown in Table XVII.

Table XVII. DISTRIBUTION OF RÉSUMÉS AND EVENTS BY ORGANIZATION CLASS

| Organization class | Events (%) | Résumés (%) |
|---|---|---|
| In-house laboratories | 43.2 | 35 |
| Industry | 43.6 | 53 |
| Universities | 10.6 | 12 |
| Other | 1.6 | 0 |

The second test, involving a time distribution study, was to compare the percentage of the total number of Events that occurred in a given year with the percentage of the résumés that applied to individuals who had made their contributions in that year. The findings demonstrate a positive correlation at the 0.93 level.[11] The résumés seem to be a usefully valid sample. The slight bias in favor of industrial performers will be considered later.

[11]Spearman's coefficient of rank correlation:

$$r = 1 - \frac{6\Sigma d^2}{n(n^2-1)}$$ where: d = difference in ranks.
n = number of items ranked.

A useful and unique characteristic of the personnel data file is that every one of the individuals whose descriptions make up the file is known to have made a utilized contribution to Defense science or technology. This factor permits useful comparisons between the HINDSIGHT contributors and the general scientific and technical communities of the nation. The unique aspect of the file is that it offers an opportunity to test a number of hypotheses regarding productivity and the consequences of managerial policy actions. Such comparisons and analyses are presented in sections 5.7 through 5.11.

## 5.7 Education

Table XVIII shows the distribution of academic degree levels among the identified contributors and comparable data for the entire national scientific and engineering community.

Table XVIII. EDUCATIONAL LEVEL OF IDENTIFIED CONTRIBUTORS

| Degree | Source of Data*: HINDSIGHT | NORC | SRI | NSF | EJC |
|---|---|---|---|---|---|
| Ph.D. | 10.5% | 3.1% | 1.2% | 3.8% | 63% |
| M.S. | 22.5% | 8.6% | 7.2% | | |
| B.S. | 57.0% | 34.6% | 47.0% | | |
| Some college | 6.8% | 39.5% | 44.6% | | 37% |
| No college | 3.2% | 14.2% | | | |

Note: *Sources of data are as follows:

NORC: S. Warkov and J. Marsh, *The Education and Training of America's Scientists and Engineers: 1962* (Chicago: National Opinion Research Center, University of Chicago, October 1965), p. 17.

SRI: A. Shapero, R.P. Howell and J.R. Tombaugh, *An Exploratory Study of the Structure and Dynamics of the R&D Industry* (Menlo Park, California: Stanford Research Institute, June 1964), p. 31.

NSF: *Profiles of Manpower in Science and Technology* (Washington, D.C.: National Science Foundation, NSF 63-23, 1963), p. 17ff.

EJC: "How Many Engineers?" *Engineering Manpower Bulletin*, No. 5, Engineers' Joint Council, New York, July 1966.

At the Ph.D. level, data from the Stanford Research Institute (SRI) are probably the most useful for comparison purposes; that is, for Ph.D., the 10.5 percent identified through Project HINDSIGHT should be compared with the 1.2 percent in the SRI column. The pharmaceutical, petrochemical, biological, anthropological and sociological fields, with their relatively heavy concentration of Ph.D.'s, markedly influence the data of the National Opinion Research Center (NORC) and the National Science Foundation (NSF); this condition is not significant in the SRI data because that related primarily to the defense aerospace community. The equipments chosen for the HINDSIGHT study mitigated against any strong contribution from these Ph.D.-heavy fields, so it is reasonable to exclude them entirely from this particular analysis.

At the M.S. level, the difference between the SRI and NORC data is probably not statistically significant.

5.7.1 Hypotheses: A comparison of the educational-level distributions with those of any other source clearly suggests that the identified contributors do not constitute a random sample of the general scientific and engineering community. Prevalence of the Ph.D. degree is more than eight times greater than would be expected; the M.S. degree, over three times greater. This observation might be explained, wholly or in part, by one or more of several hypotheses. Perhaps—

(1) there is a positive correlation between the technical nature and the amount of formal education to which an individual is exposed and his propensity for producing knowledge that is useful in defense weaponry;

(2) the personal qualities that drive an individual to seek progressively higher academic degrees are quite similar to those requisite to successful performance as a contributor of science and technology useful to Defense; or

(3) the prestige of the higher educational level places the individual in a position affording greater opportunity to perform.

The principal findings of Project HINDSIGHT (as presented in section 4) develop a strong case for the DoD's support of directed research in science and technology. They do not—perhaps because of the more tenuous information flow and communication path between the universities and Defense engineering—make as strong an argument for continued DoD support of the less well-directed scientific investigations in the academic environment. There are good reasons for the DoD's support of university research, however, and a quantitative demonstration of their validity is possible.

An important part of the argument resides in the demonstration that the first of the foregoing three hypotheses is clearly valid and better explains the correlation between degree level and productivity. The

consequence of DoD influence on the choice of scientific area of concentration in the supported universities is manifested by the relatively greater portion of those institutions' graduates who eventually make militarily significant contributions to science and technology.

5.7.2 Sources of Education: Among the identified performers, 98 percent of the degrees were awarded by colleges or universities in the United States. The remaining 2 percent, awarded by foreign institutions, were almost exclusively Bachelor's degrees, B.S. or B.A. In 1959, approximately the year of the median Event considered in Project HINDSIGHT, the university-trained scientific and engineering manpower of the United States was slightly in excess of 1.09 million people.[12] Of these, about 20,000 were immigrants who had received their education abroad.[13] Thus, on the assumption that there is no correlation between source of the degree and propensity for productivity in defense-oriented science and technology, it would be expected that about 2 percent of the identified performers would have received their degrees at foreign universities—precisely the finding of this study insofar as the B.S./B.A. level is concerned.

The B.S. degrees awarded in the United States came from more than 70 colleges and universities. The distribution among these many institutions appears to correlate solely—and then, very crudely—with the size of the university and its proximity to the industrial organizations and Government laboratories that contributed large numbers of Events. Both observations tend to support the hypothesis that prestige, or some unidentified personal characteristics, account for the disproportionately high percentage of degreed individuals among the Event performers—at least, at the B.S./B.A. level.

Table XIX lists fields of technical activity[14] represented by the identified RXD Events and shows the relative distribution of B.S./B.A. fields among the performers in each technical area. The data in this table clearly demonstrate a very marked correlation between the specific area in which the person was educated and the one in which he usefully performs. Even though degree holders in technical areas other than those closely associated with a given Event had essentially the same total exposure to formal education—and presumably the same amount of degree-conveyed prestige—as individuals whose education was within the closely associated degree area, relatively few "cross-field" accomplishments are seen. This observation is offered in partial support of the first

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[12] "Resources of Scientific and Technical Personnel in the OECD Area, 1963," *Manpower Statistics, 1954-1964* (Paris: Organization for Economic Cooperation and Development, 1965).

[13] *Scientific Manpower from Abroad* (Washington, D.C.: National Science Foundation, NSF 62-24, 1962).

[14] *COSATI Subject Category List (DoD-Extended), op.cit.*

Table XIX. PROFESSIONAL MOBILITY AT THE B.S./B.A. LEVEL

| Activity Area* / Degree Field | Mechanical engineer | Electrical engineer | Physics | Physical chemistry | Chemical engineer | Mathematics | Industrial engineer | Aeronautical engineer | Chemistry | Metallurgical engineer | Ceramics engineer | Biology | Organic chemistry | Nuclear engineer | Civil engineer | Nuclear physics | Education |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Aerodynamics | 5 | 1 | - | - | - | - | - | 4 | - | - | - | - | - | - | - | - | - |
| Aeronautics | 2 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - |
| Aircraft | 3 | - | - | - | - | - | - | 2 | - | - | - | - | - | - | - | - | - |
| Aircraft flight instrumentation | 2 | 4 | 1 | - | - | - | 1 | 2 | - | - | - | - | - | - | - | - | - |
| Atmospheric physics | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Administration and management | 1 | 3 | - | - | 1 | - | - | 1 | 2 | - | - | - | - | - | - | - | - |
| Documentation and information technology | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Human factors engineering | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Man-machine relations | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Weapon effects | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| Chemical engineering | - | - | - | - | 3 | - | - | - | 2 | - | - | - | - | - | - | - | - |
| Physical chemistry | - | - | - | - | 1 | - | - | - | 1 | - | - | - | - | - | - | - | - |
| Components | 3 | 14 | 3 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Computers | 1 | 11 | 2 | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| Electronic and electrical engineering | 1 | 7 | 7 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Information theory | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Subsystems (electronic) | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Power sources | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Energy sources | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| Adhesives and seals | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| Ceramics, refractories and glasses | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - |
| Coatings, colorants and finishes | - | - | - | - | 2 | - | - | - | 1 | - | - | - | - | - | - | - | - |
| Metallurgy and metallography | 4 | - | 1 | - | - | - | - | - | 1 | 3 | - | - | - | - | - | - | - |
| Miscellaneous materials | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |

Notes: Figures indicate relative frequency of occurrence within the row.
*Arranged according to the *COSATI Subject Category LIST (DoD-Extended)*, op. cit.

Table XIX. PROFESSIONAL MOBILITY AT THE B.S./B.A. LEVEL (continued)

| Activity Area / Degree Field | Mechanical engineer | Electrical engineer | Physics | Physical chemistry | Chemical engineer | Mathematics | Industrial engineer | Aeronautical engineer | Chemistry | Metallurgical engineer | Ceramics engineer | Biology | Organic chemistry | Nuclear engineer | Civil engineer | Nuclear physics | Education |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Oils, lubricants and hydraulic fluids | - | - | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| Rubbers | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| Mathematics and statistics | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - |
| Operations research | 1 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - |
| Machinery and tools | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Marine engineering | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Pumps, filters, pipes, tubing and valves | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Safety engineering | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Structural engineering | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Laboratories, test facilities and test equipment (mechanical) | 5 | - | 1 | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| Reliability | 2 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Missile launching and ground support | 8 | 1 | 2 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Missile trajectories | 2 | 2 | - | - | - | 2 | - | 1 | - | - | - | - | - | - | - | - | - |
| Missile warheads and fuzes | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| Missiles | - | 4 | 1 | - | 2 | - | - | 2 | - | - | - | - | - | - | - | - | - |
| Communications | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Direction finding | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Magnetic detection | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Navigation and guidance | 1 | 6 | - | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| Optical detection | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Nuclear explosions | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Nuclear instrumentation | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

Table XIX. PROFESSIONAL MOBILITY AT THE B.S./B.A. LEVEL (continued)

| Activity Area / Degree Field | Mechanical engineer | Electrical engineer | Physics | Physical chemistry | Chemical engineer | Mathematics | Industrial engineer | Aeronautical engineer | Chemistry | Metallurgical engineer | Ceramics engineer | Biology | Organic chemistry | Nuclear engineer | Civil engineer | Nuclear physics | Education |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ammunition, explosives and pyrotechnics--- | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Combat vehicles--------------------------- | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Explosions, ballistics and armor---------- | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Fire-control and bombing systems---------- | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Rockets----------------------------------- | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Underwater ordnance----------------------- | 15 | 8 | 2 | - | - | - | - | - | 1 | - | - | - | - | - | - | - | - |
| Fluid mechanics--------------------------- | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Masers and lasers------------------------- | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Optics------------------------------------ | - | 2 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Particle accelerators--------------------- | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Particle physics-------------------------- | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Thermodynamics---------------------------- | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Wave propagation-------------------------- | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Fuels------------------------------------- | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - | - | - | - |
| Jet and gas turbine engines--------------- | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Rocket motors and engines----------------- | 7 | - | - | - | - | - | 1 | 1 | 1 | - | - | - | - | - | - | - | - |
| Liquid rocket motors---------------------- | 2 | - | - | 1 | 5 | - | - | 2 | 3 | - | - | - | - | - | - | - | - |
| Astronautics------------------------------ | - | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Spacecraft-------------------------------- | 1 | - | 3 | - | - | - | - | 1 | - | - | - | - | - | - | - | - | - |
| Spacecraft trajectories and reentry------- | 3 | - | - | - | 1 | - | - | 1 | - | - | - | - | - | - | - | - | - |
| Space launch vehicles and ground support-- | 1 | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

hypothesis stated above—that there is a positive correlation between the technical nature and amount of formal education to which an individual is exposed and his propensity for producing useful knowledge.

Additional support for this hypothesis is obtained by considering the sources of the M.S. and Ph.D. degrees held by the identified performers. Although the Department of Defense has supported research in about 200 colleges and universities throughout the United States, the larger share of this support has gone to a relatively small group of them. If the research efforts supported by the DoD were closely related to the technical areas of defense weaponry, and if there is a correlation between nature and amount of formal education and propensity for producing useful knowledge, there should be a correlation between the amount of DoD funding support received and the number of identified performers graduated. That is, the universities heavily involved in defense-oriented research should be producing a relatively greater number of scientists and engineers with a defense-technology orientation than those concentrating their research activities more heavily elsewhere.

Considering first the identified performers who have been awarded a Ph.D.: The top 23 universities, in terms of support received from the DoD for research, awarded approximately 25 percent[15] of the Ph.D.'s in the physical sciences and engineering during the period of primary interest to the HINDSIGHT study. Slightly in excess of 50 percent of the identified performers, or a factor of more than 2:1 over random expectation, received their highest level degrees from those universities.

At the M.S. level, a similar situation exists. In this case, the same universities awarded about 31 percent[16] of the degrees in the United States, but 46 percent of the identified performers received their degrees from them.

As these are the larger and generally the better known of the American universities, they undoubtedly have a strong appeal for the better students. It is quite likely, therefore, that the findings just described are influenced by factors other than simply the relative amount of research supported by the DoD. In particular, the phenomenon, "quality seeks quality," can be suspected of affecting the entering student. Nevertheless, there is such a marked correlation between the level of DoD-supported research and the relative production of scientists and engineers useful to the DoD that the hypothesis of interest certainly appears to be supported; clearly, the nature of formal education is important.

[15] Privately requested data from the National Science Foundation.

[16] *Ibid.*

5.7.3 Consequences of DoD Support of University Research: At this point in the consideration of the three hypotheses stated in section 5.7.1, another matter of interest should be noted. The introduction of this report (section 1) offered a hypothesis based on comments by critics of certain DoD policies:

> The support of scientific research in the universities, by the Department of Defense and at current funding levels, significantly affects the availability of the best faculty talent to teach students.

If this hypothesis were substantially true, it would be expected that graduates of the less heavily supported universities would benefit—that, because the university devoted its better faculty to teaching them, the graduates should have acquired a better education and, everything else being equal, should show up more frequently in studies such as this. Clearly, such was not the case during the time frame in which the identified performers received their formal education. The universities that were most heavily engaged in DoD-supported research also produced a disproportionately high share of the scientists and engineers who were important to the DoD.

Further, inasmuch as the level of DoD funding in support of university research has not grown during the past few years as rapidly as either (1) total Federal support of research in the universities or (2) graduate education in the United States, it is most doubtful that the hypothesis would be any more valid today.

## 5.8 Military Service

In section 4, the argument was developed that the recognition of a need is an important precursor to the production of utilized scientific or technical information. It is reasonable, then, to suspect that exposure to the military environment might serve to introduce an individual to the needs of the services and place him in a favored position to make a contribution. If true, this proposition could become of considerable value by providing an additional selection criterion for employment in the defense research and development community.

In the sample of identified performers, the roughly even division of those who had military experience and those who had none suggests that, at least to a first-order approximation, exposure to the military environment may not be a significant factor. But the prospects of this proposition are so appealing that a more detailed examination of the available data is warranted (section 5.8.1); moreover, the proposition sheds further light on the hypotheses of section 5.7.1.

In addition, two possible tests for other differences between the military veteran and nonveteran populations involve relative educational and age levels at the time of contribution (sections 5.8.2 and 5.8.3).

5.8.1 Nature and Length of Service: If a correlation exists between military service and the probability that the person involved will produce militarily useful technology, it is obvious that the precise nature of the military role he played would be significant. In that vein, 51 percent of those reporting previous military service claimed that the nature of their assignments was such as to contribute to their future occupation. These general statements are substantiated by the high percentage of military job titles such as "radio and radar maintenance," "electronics technician," "ordnance technician," "aircraft maintenance," and the like among those who reported in that detail.

Other aspects of the veteran performers' association with the military services lend further support to the argument that they are not a normal, or random, segment of the population. Based on population distributions, approximately 10 to 12 percent could have been expected to be commissioned officers; in fact, 40 percent were commissioned prior to separation from service. Of that group, 53 percent served during World War II, and 47 percent, between 1947 and 1963. Similarly, of those who served as enlisted men, 56 percent were in the armed forces during World War II, and 44 percent served during the period 1947-1963.

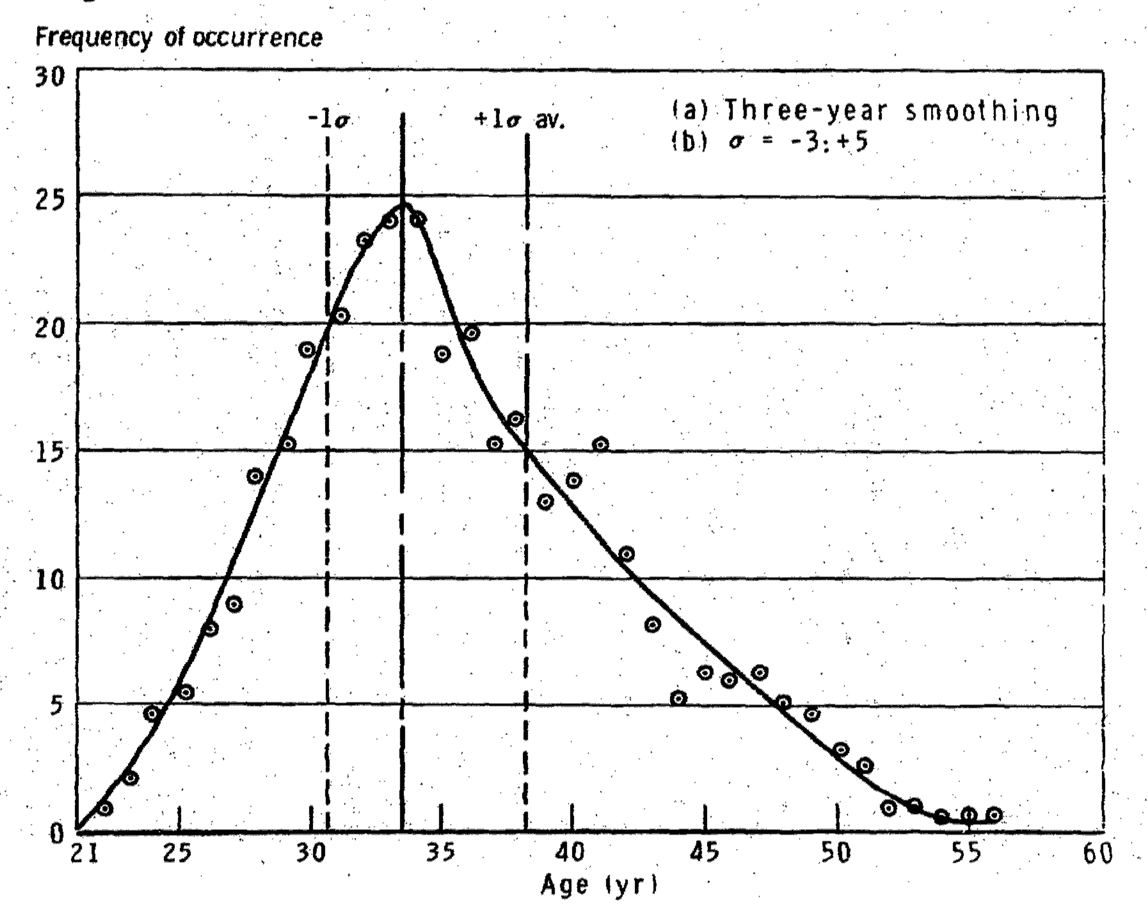
With the exception of a few people who apparently were called into military service quite early in World War II and served until the end of hostilities, the identified performers tended to have 2 or 3 years of service. Approximately 51 percent of those with military experience reported 2 years or less; 86 percent reported 3 years or less.

Thus, a "typical" veteran performer might be described as a young enlisted technician or a technical officer. He had bench-level experience with military equipment and a real opportunity to become familiar with special design or other requirements imposed on equipment by the military environment. This suggests that these veterans may well have gained a favored position, which constitutes an obvious advantage.

5.8.2 Educational Level—Veteran vs. Nonveteran: There are interesting differences in the distributions of graduate degrees held by nonveterans and veterans, the latter subdivided into two groups—commissioned officers and enlisted men. These distributions, shown in Table XX, suggest that the commissioned veteran was more apt to have a higher degree than either the nonveteran or the enlisted veteran, in that order. This ordering, although not denying that military service had put the individual in a favored position to perform usefully, tends to support the second hypothesis of section 5.7.1. In fact, it appears that the hypothesis can be extended as follows: The personal qualities that drive an individual to seek successively higher academic degrees *and military rank* are quite similar to those requisite to successful performance as a contributor of science or technology useful to defense.

During the information-collecting phase of Project HINDSIGHT, no attempt was made to ascertain the reasons for the differences between the enlisted veterans or all veterans and the nonveterans. However, a plausible explanation can be conjectured. First, it is quite likely

## Figure 15. AGE OF PERFORMER AT TIME OF CONTRIBUTION



that, in a number of cases, cause and effect can be interchanged; that is, it may be suspected that at least some of those who earned graduate degrees were, as students, held by their Selective Service Boards in a deferred status until after graduation. By then, many effectively avoided military service because of marital status, relatively advanced age or special employment. Second, many of the performers who had their advanced degrees before World War II were draft deferred because of important scientific and technical assignments vital to the national war effort.

Table XX. DEGREE DISTRIBUTIONS: VETERANS AND NONVETERANS

| Degree Level | Veterans | | | Nonveterans |
|---|---|---|---|---|
| | Officer | Enlisted | All | |
| Postdoctoral | 1.4% | 1.0% | 1.2% | 0.4% |
| Ph.D. | 11.1 | 5.5 | 8.1 | 10.9 |
| M.S./M.A. | 25.0 | 19.6 | 21.5 | 22.9 |
| B.S./B.A. | 55.5 | 59.4 | 57.3 | 56.7 |
| Some college | 5.6 | 10.3 | 8.6 | 5.7 |
| Technical school | 0 | 1.4 | 1.0 | 1.7 |
| High school only | 1.4 | 2.8 | 2.3 | 1.7 |

It was noted in section 5.7 that there is a correlation between level of academic education and propensity for advancing the state of the art of military science and technology in a useful manner. The arguments presented in the foregoing several paragraphs suggest that practical experience with military equipments, or perhaps attendance at one of the military services' schools in preparation for such an assignment,[17] tends to give a measure of equalization. This explanation would rationalize the generally lower educational level of the enlisted veteran, who is the one most likely to have taken a course at a highly specialized technical service school. Further, it supports the hypothesis that a correlation in fact exists between nature as well as level of education and tendency to perform usefully in Defense R&D.

5.8.3 Age at Time of Contribution—Veteran vs. Nonveteran: An examination of relative age distributions, veterans vs. nonveterans, at the time a contribution was made produces inconclusive results. Some veterans completed all or part of their education before entering the military service. Others started undergraduate or graduate work after leaving the service. Among all performers, as shown in Figure 15, there was considerable spread in age at the time of contribution. The interquartile range of what approaches a Poisson distribution is (-)3 and

[17]This information was not solicited; because of the known tendency of the services to give special schooling to technicians, however, the possible impact of this factor cannot be ignored.

10½ years, a period in excess of the typical 2- to 3-year service of the veteran. Thus, it is reasonable to find little significant difference between the productive ages of veterans and nonveterans.

## 5.9 Mobility

Mobility of scientific and technical personnel can be described in several different ways. There is "professional mobility," the propensity of an individual for crossing the loosely recognized boundaries of scientific disciplines or areas of technology (section 5.9.1). More familiar is the "interorganizational mobility" associated with professionals' movement from one to another of the various employers of scientific and technical expertise (section 5.9.2). There is also "intraorganizational mobility," as a person changes the nature of his work within a single organization, i.e., changes other than those involving scientific or technical areas of interest (section 5.9.3).

Of these three forms of mobility, only interorganizational movement is known to have been studied to any great depth. Shapero and others investigated the movements of several thousand scientists and engineers, primarily of the aerospace research and development community.[18] To a limited extent, the characteristics of the individuals identified through Project HINDSIGHT can be compared with the SRI findings.

In the following sections (5.9.1 through 5.9.4), HINDSIGHT data are further analyzed to continue testing the hypotheses presented earlier and to provide a base line for future studies of the behavior patterns of scientists and engineers.

5.9.1 Professional Mobility: This kind of mobility was defined in the foregoing paragraphs as the propensity of an individual for crossing the loosely recognized boundaries of scientific disciplines or areas of technology. A measure of the professional mobility of the identified performers is obtained through analysis of the matrix in Table XIX, a comparison of the fields of technical activity represented by the RXD Events with the relative distributions of degree fields at the B.S./B.A. level among the performers associated with each technical activity.

For purposes of analysis, professional mobility is further defined as encompassing the expectation that a given individual will make a significant scientific or technical contribution in a field other than that for which he was prepared by formal education. That expectation, then, is measured simply as the ratio between (a) the number of individuals who, because of degree field, might normally be expected to make no contribution in a specific area and (b) the total number of individuals making contributions in that area.

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[18] *R&D Studies Series* (Menlo Park, California: Stanford Research Institute, 1965-1966).

From the same raw data that provided Table XIX, a professional-mobility index for performers with B.S. or B.A. degrees is calculated to be 0.17. Similar calculations for performers whose highest degree is M.S. or M.A. result in a mobility index of 0.13. For the Ph.D. level, an index of 0.04 is found. Thus, expected mobility at the M.S./M.A. level is more than three times greater than it is at the Ph.D. level; and about four times greater at the B.S./B.A. level.

The rank ordering of this finding is not at all surprising. The realization that the data suggest that only some 4 percent of the Ph.D.'s can be expected to make contributions outside their originally chosen fields, however, suggests that Ph.D. training within U.S universities is quite narrow.

In part, perhaps, this finding—the lack of professional mobility on the part of Ph.D.'s—explains the earlier finding of a correlation between DoD-supported research in universities and the defense orientation of those universities' graduates. The degree fields shown as the abscissa of Table XIX are obviously quite broad. Within these fields, each Ph.D. candidate selects some subfield for specialization. If he is influenced in this choice by a faculty adviser engaged in DoD-sponsored research, if his research is oriented to military uses, and if his mobility (i.e., movement) from the subfield is little greater than it is from the general field, it is not surprising that he is found later to be making a useful contribution to science or technology significant to the DoD.

These arguments further support the first hypothesis of section 5.7.1 that there is a positive correlation between the technical nature and the amount of formal education to which an individual is exposed and his propensity for producing knowledge that is useful in defense weaponry.

Realizing that the faculty for an M.S. degree candidate is, to a considerable extent, made up of the Ph.D. candidates just mentioned and their faculty advisers, it is almost to be expected that the M.S. candidate would become "defense oriented."

Why the M.S. degree from a university where the DoD supports research is relatively so much more prevalent among the identified performers than the Ph.D. degree is not readily apparent. One possibility that cannot be discounted is that exposure to a defense-oriented faculty has caused a greater than average percentage of graduates from these universities to seek employment in the defense industries. This matter is researchable; such a project may already have been undertaken, but, if so, the findings have not been widely circulated.

Another but more subjective measure of the lack of professional mobility among the identified performers may be seen by comparing Table VIII (a list of the scientific and technical areas involved in RXD Events), in terms of frequency of occurrence, with Table XXI, which shows the distribution of degree fields by educational level. In

addition, Table XXI gives the current distribution of the defense R&D work force in the Los Angeles area as determined by the Stanford Research Institute.[19]

Table XXI. DISTRIBUTION OF DEGREE FIELDS BY EDUCATIONAL LEVEL

| Field | HINDSIGHT sample B.S. | M.S. | Ph.D. | Los Angeles area (all degrees) |
|---|---|---|---|---|
| Electrical engineering | 30% | 33% | 19% | 23.4% |
| Mechanical engineering | 26 | 16 | 7 | 18.7 |
| Physics | 15 | 21 | 18 | 7.1 |
| Chemical engineering | 7 | 5 | 7 | ( 5.4 )* |
| Chemistry | 7 | 3 | 0 | ( ) |
| Aeronautical engineering | 6 | 5 | 5 | 12.4 |
| Mathematics | 3 | 12 | 14 | 7.5 |
| Metallurgical engineering | 1 | 2 | 0 | 0.9 |
| Civil engineering | 1 | 1 | 0 | 2.0 |
| Industrial engineering | 1 | 1 | 0 | 1.1 |
| Physical chemistry | 0.5 | 1 | 7 | NS§ |
| Nuclear engineering | 0.5 | 0 | 0 | NS |
| Nuclear physics | 0.5 | 1 | 0 | NS |
| Education | 0.5 | 1 | 0 | NS |
| Biology | 0.5 | 0 | 14 | 0.5 |
| Organic chemistry | 0.5 | 1 | 2 | ( ) |

Notes: Columns do not add to 100 percent because of rounding.
*( ) — Included within chemistry.
§NS — Not shown separately.

With the primary exception of the aeronautical engineers, the distribution in the Los Angeles R&D complex is seen to correlate reasonably with that of the HINDSIGHT performers. The exception undoubtedly is occasioned by the prevalence of the aerospace industry in that area. Again, as in Table VIII, Table XXI offers some guidance on the relative numbers of scientists and engineers (by discipline) that will be required in the near future, assuming no major change in the nature of the equipments to be developed for the military services.

5.9.2 Interorganizational Mobility: It was noted previously that the biographical sketches of the contributors identified through Project HINDSIGHT were collected during 1966 and were current as of that date. Thus, it is possible to examine the interorganizational mobility of

[19]A. Shapero, R.P. Howell and J.R. Tombaugh, *The Structure and Dynamics of the Defense R&D Industry: The Los Angeles and Boston Complexes* (Menlo Park, California: Stanford Research Institute, November 1965), p. 24.

those people over a long period of time—in some cases, as much as 40 years. In Figure 16, the sample of performers is examined with respect to total years of professional civilian experience vs. frequency of occurrence. Half of the sample had between 13 and 24 years of experience. The median length of employment was shown to be in excess of 16 years.

Shapero and others studied the engineer/scientist work force of the defense R&D industry in the Los Angeles and Boston areas.[20] Based on the age distribution they reported for the work force, the median length of employment for their sample appeared to be between 8 and 9 years, or about half that found for HINDSIGHT R&D people. The distribution about the median for the R&D population in the Los Angeles and Boston complexes forms a pattern very similar to that shown in Figure 16, except, of course, that it is markedly displaced toward the origin. Despite the obvious considerable difference in average total length of professional employment, the HINDSIGHT performers appear to have made fewer total moves. Comparative data are shown in Table XXII.

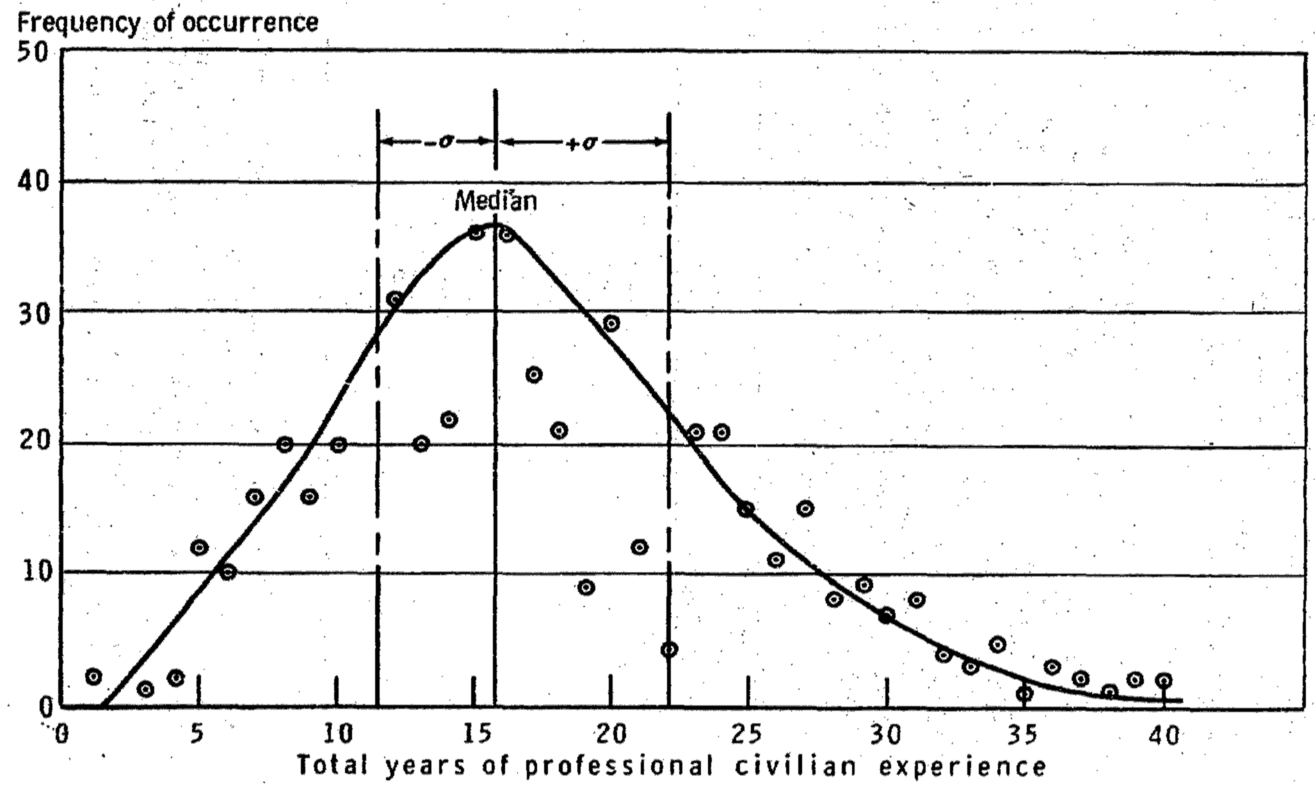
Table XXII. INTERORGANIZATIONAL MOBILITY

| No. of Previous Employers | SRI Sample | HINDSIGHT Sample |
|---|---|---|
| 0 | 24.7% | 29.2% |
| 1 | 21.2 | 26.5 |
| 2 | 17.2 | 14.7 |
| 3 | 13.3 | 19.3 |
| 4 | 9.1 | 6.4 |
| 5 | 6.4 | 3.8 |
| 6 | 4.0 | 0 |
| 7 | 2.8 | 0.1 |
| 8 | 0.8 | 0 |
| 9 | 0.2 | 0 |
| 10 or more | 0.3 | 0 |

Undoubtedly the value of many individuals identified through the HINDSIGHT studies had long been recognized by their respective employers. It certainly can be expected that whatever appreciation these employers expressed, plus whatever satisfaction the individuals derived from knowing that their work was being used, contributed to the relative stability of their employment. Nevertheless, it is interesting that the successful performer is not as prone to change jobs as his average professional associate.

[20] *Ibid.*, pp. 22 and 23.

## Figure 16. LENGTH OF EMPLOYMENT, 1966



A somewhat different cause-and-effect relationship may be inferred from this apparently low mobility, along with th data on age at the time of contribution (see Figure 15). Together, they suggest that the person had been with his employer for some time before making the noted contribution. This could mean that, because of his long service with the organization, he was in a favorable position to have his ideas recognized and exploited. The inference would be entirely consistent with the finding (section 4.3.7) that: A high combined inventiveness, or ingenuity, and utilization rate are dependent upon the time and space coexistence of four primary factors—the recognition of need, a source of ideas in the form of an educated talent pool, capital resources and an adequate communication path to potential users.

The general educational level of the contributor already has been established. Add to this the fact that, through long years of association with his company, he had acquired specialized experience in its technical affairs and had developed the ability to interpret its needs and problems. Then, only the resources that one could expect would be made available to a trusted employee are necessary to complete the four factors named in the finding.

On balance, it appears logical to conclude that it is the individual's low interorganizational mobility that leads to successful performance rather than his performance that leads to job stability.

5.9.3 Intraorganizational Mobility: The HINDSIGHT contributors show as little propensity for moving within a company as they do for moving between organizations. The information they submitted suggests that, on the average, each person had held two different positions within his organization. In most cases, he changed from a job calling primarily for activity in a given scientific or technical field to an assignment chiefly involving management responsibility in the same technical area or one of somewhat larger scope.

This finding appears to be entirely consistent with—and possibly helps to explain—the previously mentioned finding that there is a very high degree of professional stability among the identified contributors (see section 5.9.1). To some extent, this stability may be encouraged by the fact that senior management may be reluctant to make assignment changes that would force the employee into "professional mobility," i.e., into another scientific or technical field. Of course, it may be that management merely accedes to the employee's insistence that he be allowed to remain within his chosen technical area of work.

This is a researchable question, but it was not addressed in the HINDSIGHT Task I study. A more thorough understanding of the matter would be useful, because it may be that management has inadvertently adopted a policy that mitigates against the fullest exploitation of its most creative employees.

5.9.4 Education and Responsibility: The third hypothesis in section 5.7.1 suggested that the correlation between level of education and propensity for making utilized contributions might merely be based on the fact that the prestige associated with the higher academic degree held by the individual placed him in a favored position to perform successfully.

A partial test of the hypothesis can be made by comparing educational achievement with other measures of success within the professional society. Specifically, degree level can be compared with the individual's hierarchical rank within the organization. To facilitate this test, six categories, or "responsibility/authority levels," were established, as shown in Table XXIII, and the sample of identified contributors was separated, by degree level, into those classifications with the results given in Table XXIV.

Table XXIII. RESPONSIBILITY/AUTHORITY LEVELS

| Level | Assignment |
|---|---|
| Division director | Supervision of several branches related by business or object interests. |
| Branch director | Supervision of several groups related by discipline. |
| Project manager | Supervision or coordination of two or more groups related by project. |
| Group manager | Supervision of one or more working-level people. |
| Professional | Degreed scientist or engineer at work level. |
| Semiprofessional | Technician. |

It is obvious that, in absolute numbers, the top four responsibility/authority levels are dominated by people whose highest degree was at the B.S./B.A. level. This finding is partially a consequence of the fact that the largest percentage of the identified contributors is in the Bachelor's degree group. The distributions of the managerial segment of Table XXIV can be adjusted to compensate for unequal degree-level distributions among all performers (Table XVIII), with the results shown in Table XXV.

Table XXIV. UNWEIGHTED DISTRIBUTION: DEGREE VS. RESPONSIBILITY LEVEL

| | Education | | | | |
|---|---|---|---|---|---|
| Responsibility Level | Ph.D. | M.S. | B.S./B.A. | Some college | High school |
| Division director | 26% | 20% | 51% | 3% | - |
| Branch director | 13 | 22 | 52 | 3 | - |
| Project manager | 6 | 25 | 61 | 6 | 2% |
| Group manager | 7 | 29 | 58 | 4 | 2 |
| Professional | 11 | 20 | 61 | 6 | 2 |
| Semiprofessional | - | - | 10 | 45 | 45 |

Note: Horizontal rows add to 100 percent.

Table XXV. WEIGHTED DISTRIBUTION: DEGREE VS. RESPONSIBILITY LEVEL

| | Education | | | | |
|---|---|---|---|---|---|
| Responsibility level | Ph.D. | M.S. | B.S./B.A. | Some college | High school |
| Division director | 43% | 33% | 16% | 8% | - |
| Branch director | 34 | 28 | 26 | 12 | - |
| Project manager | 13 | 26 | 25 | 21 | 15% |
| Group manager | 15 | 32 | 24 | 14 | 15 |

At the two highest levels of authority, degree level and responsibility are seen to be positively correlated and monotonically decreasing. Recognizing that the degree fields of these individuals were science and engineering rather than management, this finding does suggest that the prestige conferred by the higher degree has an influence in achieving promotion. Or, as in the case of people with military experience, it may be that whatever personal characteristics drive one to seek higher degrees have much in common with those that impel one to seek positions of responsibility.

The distributions at the levels of project and group managers are not at all inconsistent with either or both interpretations. The data on responsibility/authority levels relate to the contributors' current positions, not their positions at the time of the RXD Event involved. Further, the length of time that most of those individuals had been employed suggests that, in the preponderance of cases, they were at or near the highest positions of authority to be expected. Thus, Table XXV demonstrates that there is a weeding-out process and that the person holding the higher degrees can expect commensurate rewards.

It is clear, however, that this analysis—intended to test the correlation between degree-conferred prestige and propensity for making militarily useful contributions to science and technology—results in equivocal findings. Prestige may be a factor, but it does not appear to be truly significant.

Further analysis of the biographical sketches suggests that interorganizational stability also correlates positively with responsibility/authority level—at least, among the identified successful performers. Table XXVI displays the relationship between number of previous employers and hierarchical level of responsibility achieved by 1966. Only management levels are considered.

Table XXVI. RESPONSIBILITY/AUTHORITY LEVEL VS. NUMBER OF PREVIOUS EMPLOYERS

| Responsibility/ Authority Level | No. of Previous Employers | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 or more |
| Division director | 28% | 19% | 28% | 18% | 4% | 3% |
| Branch director | 32 | 21 | 22 | 6 | 10 | 9 |
| Project manager | 33 | 26 | 17 | 10 | 9 | 3 |
| Group manager | 34 | 33 | 11 | 14 | 5 | 3 |

Note: Percentile by row.

Comparison of the information in Tables XXV and XXVI suggests that, at the division-director level, some tradeoff is accepted between the Ph.D. degree and number of previous employers. That is, at this highest level the Ph.D degree is somewhat more important than interorganizational stability as a criterion for promotion. This is additional evidence that prestige associated with degree level correlates with the attainment of positions of higher responsibility and authority. It is noted, however, that this particular finding is not necessarily relevant to the hypothesis concerning nature and level of education and propensity for useful contribution.

## 5.10 Marital Status

For the current engineering and scientific work forces of the Boston and Los Angeles R&D complexes, Shapero and others reported that 70.9 percent of the males were married, 27.3 percent were single, and 1.8 percent were divorced or separated at the time they were hired.[21] The somewhat higher average age of the HINDSIGHT contributors at the time their biographical sketches were collected (43 vs. 36 years) precludes a useful comparison. Nevertheless, the differences are great enough to warrant reporting. The distribution among the HINDSIGHT contributors was found to be:

Married---------------94.0%  Widowed--------0.4%
Single---------------- 4.9%  Ever divorced--4.0%
Divorced or separated-- 0.7%

[21] *Ibid.*, p. 26.

It is primarily the difference in the "divorced or separated" figures, despite the relatively small percentage in either case, that may be most interesting. The repeatedly noted tendency toward stability —in terms of areas of professional interest, in terms of employers, in terms of positions within an organization—is further evidenced by the apparently greater marital stability of the successful contributor.

### 5.11 Continued Postgraduate Education

In addition to formal education leading to the award of a degree, many of the contributors reported attending one or more postgraduate courses. Well over 50 percent of the individuals participated in short courses or lectures series sponsored by their employers. The available information on these courses, which varied in length between a few hours and a few weeks, is inadequate as a basis for analysis of the quality or significance of the instruction. A somewhat smaller group reported that they had taken formal courses offered by recognized universities either on or off campus. Table XXVII presents a distribution of the latter information in terms of the highest degree held by the reporting person and by the general nature of the course.

Table XXVII. POSTGRADUATE EDUCATION

| Type of Course | Ph.D. | M.S. | B.S. |
|---|---|---|---|
| Technical | 6% | 14% | 10% |
| Administrative | 0 | 4% | 1% |

In some cases, the individual had delayed taking a formal course for as much as 20 years after receiving his last degree. The average delay appears to be about 7 years, and the median, about 5 years.

No comprehensive information concerning the practices of the defense-oriented R&D community is known to be available. There are some data on individual organizations and on the entire national scientific and engineering community, however, that offer a limited basis for comparison.

The National Science Foundation[22] estimates that about 5 percent of the country's scientists and engineers are currently taking part-time university work. From the NSF data, it is not possible to determine the total percentage that continue with postgraduate education at one time or another over the years.

[22]Zola Bronson, National Science Foundation, private correspondence, August 1967.

At the individual organizational level, I. M. Rubin[23] reports that by 1967 more than 90 percent of the professionals at the Langley Research Center, National Aeronautics and Space Administration, had taken at least one formal university course under the auspices of NASA's continuing education program, with approximately one-third of the staff participating in any recent year. At the Army's Harry Diamond Laboratories, 85 percent of the professional staff completed courses of at least one semester's duration during the period 1964-1967.[24]

By any of these measures, the identified contributors to RXD Events are markedly in the minority.

One can speculate, of course, that the contributors are leaders in their fields, and therefore are more likely to develop information to be taught their peers than to learn it in a classroom. Or it could be that the contributors tended to travel so much in the course of their work that taking even part-time classes was impracticable. Whatever the reason, it is apparent that these valuable, creative people were not given to exploiting the opportunities for continued postgraduate education that are offered by most of the larger universities.

5.12 Summary and Discussion

These additional findings combine to present extraordinarily consistent patterns. Most of the scientific and technical ingenuity and innovation leading to modern weapon systems is found in a very conservative, almost routine environment. For example, nearly half of the advances came about as a consequence of what the performers considered to be routine assignments (Table X). The persons credited with the advances give evidence of extreme conservatism. In comparison with others in their professional society, they tend more to remain in the scientific or technical areas in which they were educated, to stay on the same job with the same employer, and to be satisfied with the level of education attained before they first sought professional employment; they even tend to have more stable family lives. The chief possible departure from this otherwise consistent pattern is their apparent willingness to move from their chosen technical fields into management positions when they were relatively young.

To a considerable degree, this may explain why comparatively few of the technological Events were found to be based on the results of recent scientific advances. For is it likely that individuals with such stable and conservative traits would delve into what is, to them, the unknown for the solution to a problem? Certainly not, if such a digression

[23] I.M. Rubin and H.G. Morgan, *A Projective Study Towards Continuing Education* (Boston: Sloan School of Management, Massachusetts Institute of of Technology, 1967).

[24] Maurice Apstein, Harry Diamond Laboratories, private correspondence, August 1967.

could be avoided. If the characteristics of people making significant technological contributions in areas other than weaponry are equally conservative, there is little wonder that new scientific findings move so slowly into everyday engineering.[25]

[25]Jacob Schmookler, *Invention and Economic Growth* (Cambridge: Harvard University Press, 1966).

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# 6. RESEARCH ENVIRONMENT FOR HIGH PAYOFF

## 6.1 RDT&E Environments

Management has tended to create different environments for funding control and the decision process in the several phases of the RDT&E cycle. In addition, it is alleged that significant intellectual and sociological differences may be found between the classic organizational structures identified as "Government in-house," "university-associated" and "industrial" laboratories. Presumably some one combination of the factors making up the various environments should be more effective than others for fostering creativity and the utilization of its products.

One of the primary stated purposes of Project HINDSIGHT was to identify management factors that constructively affect the productivity of a scientific or technical research program. It is emphasized that the factors sought were those associated with the combination of creativity and use of results. Quite possibly, the optimum environment represents a compromise; it may not be the best situation for scientific creativity alone, or the best for innovation.

An immediate observation based on one of the HINDSIGHT findings (see section 4.3.1) is that the broad categorical differences between Government, university and industrial laboratories do not markedly influence productivity in terms of the emphasized combination—creativity and result usage. Similarly, the study shows that productivity is not restricted to the environments associated with the R&D categories of either research or exploratory development.

Based on the 686 RXD Events on which pertinent data are available, the percentage distributions among the Defense R&D categories were found to be:

Research----------------- 9%
Exploratory development--28%
Advanced development-----40%
Engineering development--22%
Management and support--->1%

A considerable number of Events occurred before 7 June 1962, the date on which these categories were formally established. Those Events were categorized, insofar as possible, through analysis of the circumstances in which they came about. When there was significant doubt, the Event was ignored in calculating percentage distributions. Thus, the distribution is only roughly descriptive of the situation and is of interest primarily because the peaking occurs in the advanced development category. Obviously, creativity and the imaginative application of scientific principles can be found in work relating to every phase of

the RDT&E cycle. Productivity is significantly affected either by factors common to each of the organizational and budgeting categories considered here or by different sets of factors that apply within each category.

This study was not deep enough to sense different sets of factors —if, in fact, they do exist. Subsequent paragraphs consider the findings with regard to apparently significant environmental factors. The several classes of research, from undirected scientific research through research in technology, are treated in turn, and the findings are discussed in relation to pertinent management factors that seem to be controllable by policy.

Based on the methodology employed in Project HINDSIGHT, only successes were studied. It cannot be concluded, therefore, that this "most effective" environment will ensure success; failures have happened and probably will continue to occur. Because other patterns of management have failed to exhibit as high a utilization rate, however, it must be assumed that their efficacy was lower and their failure rate, at least slightly higher.

To this point, payoff has been considered only as the recognized use of results proceeding from the research effort on a military system. Other forms of payoff were observed in the course of Project HINDSIGHT, but the establishment of their relative value to a mission-oriented agency such as the DoD is beyond the scope of this study. It is clear, however, that they do exist and, by and large, tend to be associated with generally undirected research in science. (See section 2 on HINDSIGHT objectives, strategy and methodology.)

## 6.2 Research in Science

6.2.1 Undirected Basic Research: There is very little evidence that ideas spawned during recent basic research, particularly in the so-called undirected basic research in science, as opposed to directed research (Tables III and IV), manifest themselves in improved weapon systems. In the fields of statistical analysis, other aspects of information theory, nuclear physics and polymer chemistry, a very few examples have been found in which payoff was identified in a system.

Nevertheless, it has been seen that, wherever there was a payoff of basic scientific research in terms of use in systems, its value was comparatively great. Examples are found in all solid-state electronic systems, nuclear weapons and power supplies, information processing in computers and radars, and the application of statistical sampling in quality-control techniques.

The greater payoff of undirected basic research in science identified in HINDSIGHT studies has been observed in forms other than direct weapon-system application. In terms of numbers, the gain has been in

the training of scientists and engineers who performed the directed research in basic science or in technology that led to the new weapon systems. The technique of investigation, the so-called scientific approach, that has been developed and propagated by the universities has had a tremendous observable impact.

Section 5.7 demonstrated how valuable university-trained scientists have been to the Department of Defense—in particular, those trained in universities that had defense-oriented research programs. When the DoD's recognized dependence on schooled scientists and engineers is considered, along with the fact that in a typical year (FY 1965, for example) approximately 26 percent[26] of the nation's scientific and engineering talent is engaged work that is directly or indirectly Defense supported, the magnitude of the payoff may be appreciated.

The second very useful product of undirected basic research is the instrumentation developed by the scientists in their quest for knowledge. If there is a characteristic difference between undirected and directed research in science, it is probably that the former examines all possible aspects of a phenomenon in detail, while the latter tends to be more restricted in scope, focusing on the apparently most pertinent aspects. In their desire to observe in totality, the performers of undirected basic research have developed instrumentation that is exotic and precise. The resulting devices were identified through Project HINDSIGHT as they became the tools of the applied scientist and the engineer.

The nature of a third payoff of undirected research is suspected but has not yet been well established. Often the candidate for a Master's degree in science or for a Ph.D. bases his thesis or dissertation on research into a particular characteristic of a device or material. If the results of this research in any significant amount are collated by the publishers of the commonly used engineering handbooks, this third form of payoff is established. This matter is being investigated as part of Project HINDSIGHT's more detailed studies of management factors.[27]

6.2.2 <u>Directed Basic Research</u>: No sharp line of demarcation is found between theoretical, undirected research in science and its directed counterpart. Instead there is an almost continuous spectrum, from the case in which the scientist undertakes a particular line of investigation "because it looked interesting" to a venture that is totally responsive to the request of an outsider.

[26]Estimated from the ratio of Defense spending to total national expenditures for R&D. *Reviews of Data on Science Resources* (Washington, D.C.: National Science Foundation, NSF 65-11, May 1965), 1, 4.

[27]Robert C. Mills, *Liaison Activities at R&D Interfaces—A Model; Some Empirical Results and Design Considerations for Further Study* (Evanston, Illinois: Northwestern University, June 1967).

Most of the scientific research supported by the DoD is justified by some rationale and is typically referred to as "relevant." The analysis of Project HINDSIGHT data on the use of results of directed scientific research offers support for the concept of relevancy and suggests that a rigorous definition of relevance is essential. Where results were applied, the research task tended to be relevant to a very specific technology already being used in a cruder form. In a sense, recent scientific research that has been found significant to improved weapon systems took the form of a "mop-up" effort. Engineers were employing a technology with some degree of success but didn't understand in detail how or why it worked. Scientific analysis led to a better understanding and eventually to greater exploitation of the technology.

Examples of the return on investment in scientific mop-up research were found in every weapon system studied. Problems of extracting information from contemporary radars led to filter-theory research which, in turn, led to far more capable radars. Propeller-noise problems led to cavitation-theory studies that generated the knowledge needed for designing less noisy propellers for torpedoes. Problems of combustion instability in rocket and turbine engines furnished the rationale for pertinent scientific research.

Relevant research probably results in a high payoff in utilization for two interrelated reasons: (1) The scientific research was known to be in a useful area suggested by a problem in the associated technology; and (2) a ready market for any new knowledge generated was known to exist, for in advertising their problem the engineers identified themselves as potential users. Profitable directed research, as described in the preceding examples, requires a fairly direct line of communication between the engineer and the scientist.

6.2.3 Research in Materials: Another class of research in science observed in the Project HINDSIGHT studies has had an equal or greater payoff. Well over half the identified technological advances clearly occurred in the absence of new scientific ideas. Almost all, however, depended upon the existence of new information on characteristics of materials or the operation of devices such as the transistor. The class of research that leads to new materials, to measurements of those materials' characteristics, and eventually to the publication of pertinent data has been of primary value.

From the pragmatic view of a mission-oriented agency, fairly stringent criteria for the class of research leading to reference texts and handbooks can be established. The producers of the documented information, or their managers, must remain aware of the technical problems of the engineering community. Further, deliberate attempts must be made to anticipate information needs, particularly as the engineer begins to push the state of an art to its limit.

Section 5.1.2.2 discussed the importance of identifying, publishing and disseminating information regarding the characteristics of new

materials. In this particular example, the information is amenable to presentation in a handbook. But the concept involved—that of deliberately investigating natural phenomena and reporting the results in whatever form is required for maximum utility to the engineer—can be applied with equal validity in any scientific discipline.

6.2.4 General Observations: It must be remembered that all identified RXD Events have two common characteristics: First, as a consequence of research in science or in technology, some new knowledge was made available. Second, this new knowledge was employed by an applications engineer in the design or development of a weapon system or piece of military equipment.

None of the findings or observations presented in this report should be interpreted as claiming that undirected research in science during the past 20 years has not produced a great deal of useful information. Rather, the findings suggest that the transfer of undirected basic research to technology for weapon-system development can require 20 years or more. This transfer of the scientific base may be influenced by early recognition of a need or technological opportunity, by effective coupling between the scientific and technical communities, and other variables that require further definition and analysis.

The data from this study indicate, however, that there does exist a shorter time span between scientific discovery in directed basic research and its practical utilization than between undirected basic research and its practical utilization; this should be expected. The median time between the occurrence of scientific events identified in the directed basic research category and the incorporation of the resulting new knowledge into the design of a weapon system was nine years. Thus, it is evident that a motivation toward system application influences the time for transfer of basic research events into system development. This observation in no way derogates the continuing requirement for expanding the frontier in the scientific disciplines.

It is clear that, on a time scale of 50 years or more, undirected scientific research has been of immense value. Without basic physical science, we could scarcely have developed the modern technologies of nuclear energy or communications or the current electrical and chemical industries. None of the identified scientific Events would have been possible without the use of one or more of the great systematic theories —classical mechanics, thermodynamics, electricity and magnetism, relativity and quantum mechanics. These theories also played an important role in many of the technological Events. For example, if one were to count how many times Newton's laws, Maxwell's equations or Ohm's law were used in the systems studied, the total would far outnumber the recent RXD Events identified.

In less than 5 percent of all identified RXD Events, scientists or engineers were called in to "make someone else's solution work." In

85 percent of the cases, a fundamental problem was presented to the creative individual or group and a new and successful solution was conceived. The evidence is so overwhelming that no question should remain regarding the role of the scientist or research engineer vis-à-vis the applications engineer; neither can be subservient to, or unaware of, the other. Each performs best when free to cope with the fundamental problem. Any environment that enhances coordination would encourage the higher payoff of research. These general observations, by suggesting specific fruitful activities, implicitly recognize this fact.

## 6.3 Research in Technology

6.3.1 Subclasses: General and Restricted: Of the identified RXD Events, 91 percent are reasonably classified as research in technology. The characteristic that distinguishes that kind of effort from the equally important but somewhat more pedestrian work of applications engineering is the relative amount of technological risk involved. Before an RXD Event could be so classified under Project HINDSIGHT, there had to be evidence that the performers, though confident in their prospects, realized that success was not a reasonable certainty. More specifically, experiments to establish feasibility must have been designed and actually performed.

Again, as in the case of directed scientific research, two significant subclasses of highly productive utilized research in technology were observed, both involving before-the-fact recognition of a technological problem. They differ primarily in the manner in which the problem area is identified. For purposes of classification, they are described in this discussion as "general" and "restricted" technological research.

*General technological research:* In the first subclass, the performer's attention was focused on a broad spectrum of functionally similar general-purpose technological building blocks. Outstanding examples included work supported by the DoD laboratories that led to a multiplicity of transistors with selective, highly predictable characteristics and economical techniques for their manufacture and production; small compatible passive electronic devices; ferrous and nonferrous structural materials and fabrication techniques; liquid and solid rocket propellants; and explosives.

*Restricted technological research:* The second subclass covered the development of devices or techniques with fairly restricted applications. It included such items as the investigation of missile-launcher design, the development of engine and missile-motor components, and specific missile-guidance components of inertial quality.

In terms simply of the number of RXD Events identified in each subclass, 30 percent of all the technological-research Events studied were general, and 70 percent were restricted. (The matter of the subclasses' relative value is discussed in section 6.3.4.)

6.3.2 Management Aspects: Differentiating between the subclasses from a management viewpoint, we find in the "general" subclass a low risk that research results will not be used as long as the product in any way represents an advance in technology. But, without very close coordination or centralized management, there is a high risk of duplicative research efforts. In the "restricted" subclass, on the other hand, there is a comparatively low risk of duplicative efforts and a high risk of nonutilization unless the applications engineer is aware of the results and they very closely satisfy his requirements.

The ideal, efficient environment is one in which performers of restricted technological research and applications engineers are geographically or organizationally associated. Thus, general research can be performed most efficiently under centralized management, and restricted research, under decentralized management.

The value of decentralized management for the restricted subclass is confirmed historically by observing the absolute magnitude of the utilized results of technological research in the course of engineering development. From 20 to 30 percent (varying among the weapon systems studied) of the requisite new information in restricted technological research that was used had been generated during engineering development.

6.3.3 Kinds of Payoff: The examples of payoff from general technological research form a readily distinguishable pattern. The most obvious characteristic is that the technology tends to have peculiarly military flavor—or, at least, at the time the Event occurred, interest in the technology was found primarily within the Military Services. But most of the utilized technological research in guidance, radar and rocket propulsion was directed and performed by individuals who were concerned more with the technology than with the development of any specific end-item system.

In each case, however, the performers were sufficiently aware of the technology's deficiencies in terms of foreseeable requirements of future systems. This awareness extended to the knowledge of quite specific design criteria that were desired. For example, those groups pushing microwave power tubes for radar knew more than the simple fact that devices with higher output would be wanted. They had a quantitative notion of just how much higher the output would have to be.

In retrospect, it is clear that this quantitative information must have enhanced the realized research efficiency, if only by automatically ruling out any technological approaches (even if otherwise successful) whose potential was inadequate to satisfy the criteria. Examples (other than the amplitron microwave power tube already mentioned) are the hydrogen thyratron, inertial-quality guidance components, liquid and solid propellants, rocket-motor cases and magnetic sensors.

A slightly different illustration of utilized technological research is found in the development of tantalum capacitors and high-core-permeability inductors. It was obvious to key personnel that the smallness of the transistor could not be fully exploited if the size of the circuit chassis were dictated by the use of comparatively large condensers, coils and transformers. Because these people and their close associates were vitally interested in reducing the size of electronic equipment, technological research to that end was successfully pursued.

It may be that other research engineers, more remote from applications engineering, also recognized the problem and achieved technological success along other approaches. If so, no evidence of those results' utilization was found in the HINDSIGHT study. There may have been technological success, but the results were not "sold," and the research engineer's remoteness from the applications engineer cannot be discounted as the reason for it.

In over 93 percent of the identified Events in the technological research category, available information supports the conclusion that continuing interaction between research and applications engineers is essential to a productive technological research program.

Incidentally, such examples as the microwave power tube, the hydrogen thyratron and the tantalum capacitor point out a very valuable contribution by the technical personnel of the DoD laboratories. In each case, the greater part of the technological research by far was accomplished in private industry, generally under contract with one of the Military Departments. The work was distributed widely in time and place. The only names that appear with any regularity as having been involved technically are those of a few individuals from the Army Electronics Laboratories at Fort Monmouth, New Jersey, the Navy Electronics Laboratory at San Diego, California, and the Air Force's Avionics Division at Wright-Patterson Air Force Base, Ohio. It is clear that these few people provided the continuity and effective guidance that resulted in the high payoff of technological research.

6.3.4 Relative Value of Subclasses: It has been noted that 30 percent of the technological Events fell into the general subclass.

According to the analytical technique used in Project HINDSIGHT, it is assumed that each Event deserves equal weight, or value. This assumption is, in fact, valid only in the context of a single weapon system. In that case, because greatly improved weapon systems appear to be the synergistic consequence of many (usually on the order of 100 to 200) separately identifiable Events, each contributing a negligible degree of improvement, the averaging process is reasonable.

When the consequences are manifested in a number of weapon systems, which is the tendency in the case of general Events, the true value of that Event must be greater than that of one contributing only to one

system. Theoretically, of course, if every weapon system and equipment in the Defense arsenal were analyzed and the contributing Events identified, it would be possible to assign to each Event a quantitative measure of value.

During the Project HINDSIGHT study, 20 systems were sampled with varying degrees of thoroughness. On that basis, such quantitative measures cannot be made. The sample size is adequate, however, to measure the relative efficacy of general as opposed to restricted technological research. Over 12 percent of the identified Events in general technological research had an impact on more than one of the systems studied. Where this situation obtained, it was generally found that results were utilized in three or more systems. With respect to more restricted technological research, the use of results in multiple systems was recognized in 8 percent of the Events, and then infrequently in more than two systems.

6.3.5 Planning for High Payoff: The many observations on characteristics of utilized technological research arising from the HINDSIGHT systems study could be used to provide guidance for senior research management. Where anticipated results of the research are considered broadly applicable and the estimated cost of the task is comparatively low, full authority to plan and implement the research program should be vested in the scientific and engineering community interested in the pertinent technological area. Conversely, where the apparent applicability is more restricted and the task's estimated cost is relatively high, the interests of the system-oriented engineering community should be dominant.

The chief possible exception, of course, is a situation in which the initial cost of acquiring a facility for technological research of general application is very high. Management must then judge whether the application cost is properly attributable to a few tasks or whether it should properly be allocated to a great number of research efforts planned for the future.

Again, with this general exception, it appears that there is greater assurance of a high payoff from the more expensive research tasks if the systems-engineering community has some responsibility for research planning. It was observed in this study that some 20 to 30 percent of requirements for new technological knowledge—in the case of MINUTEMAN II, up to 75 percent—are established while a weapon system is being developed, which demonstrates that, at present, the systems-engineering community cannot forecast all its needs.

An apparent solution is to have greater recourse to the current R&D category of advanced development. Useful prototype weapon systems should be designed, developed and built for the express purpose of giving focus and spur to the growth of technological knowledge. This concept is not new. Whether fortuitously or by intention, it has been used to great advantage, and its impact is seen through "hindsight."

Thus, in retrospect the tremendous value of the NAVAHO missile development is recognized. There were a number of reasons that the NAVAHO never became operational, paramount among which was the appearance of the intermediate-range and intercontinental ballistic missiles. Work on the NAVAHO continued throughout essentially the whole RDT&E cycle, however, and did provide a quantitative focus for all the technologies required to support its development. It is also noteworthy that, at the start of their development, both the ballistic missile and the NAVAHO were considered high technical risks.

Studies of the technological basis for modern guided missiles (such as MINUTEMAN and POLARIS), aircraft and nuclear submarines almost invariably find their way back to or beyond the NAVAHO program. Inertial navigation and guidance systems, stellar navigation systems, flightborne digital computers, liquid rocket engines—all have been traced back to work identified as originally done for NAVAHO.

In a similar vein—though less dramatic and on a lower cost scale—a study of the history of the LANCE missile system establishes the value of the Missiles "A" and "B" programs in the 1950s. Again, requirements to advance the state of the art established by operational specifications for these developmental missiles spurred the growth of relevant technologies.

A more specific example is the contribution of the Army's DART antitank missile, which was never produced. To be economically feasible, the DART's roll-reference unit had to be provided for a fraction of the cost of available gyroscopes. As a result, part of the technological work on inertial guidance components was turned away from the quest for ever-increasing precision and focused on the need for marked cost reduction. In the absence of such motivation, it is unlikely that the quite reliable, reasonably precise, very inexpensive gyro used in the BULLPUP would have been readily available for it and for other missiles as well.

These examples and numerous others that have been identified through Project HINDSIGHT studies indicate the wisdom of undertaking system-development projects in a conscious attempt to focus exploratory development on programs of research in technology. Advanced systems would then be described in terms of operational characteristics and categorized as advanced developments. Maximum freedom should be granted the project director to seek advanced technical solutions, and at the outset there should be only limited definition of a production objective—preferably, none.

In principle, the planning inputs required for a high payoff of the general and restricted subclasses of technological research are quite different. It is possible to identify real-world problems for the former by examining classes of weapon systems—submarines, aircraft, missiles, armored vehicles—and recognizing that the growth of specific areas of technology is essential to the marked improvement of one or more of those classes.

For example, it is obvious that a submarine's depth performance is limited by the strength-to-weight ratios of available pressure-hull materials and by fabrication techniques. For aircraft, the achievement of greater effective operating speed depends upon the availability of thermally less sensitive skin materials, as well as better understanding of aerodynamics technology. To gain greater precision and longer range, artillery weapons require more efficient propellants, reduced manufacturing tolerances in projectile characteristics, less tube erosion, and so on.

Because such problems are relatively easy to identify and research results may be applied to many systems. the inherent probability that the knowledge will be used is high. Further, duplication of research can be safely minimized if planning responsibility for a technological area is centralized within a management that is thoroughly aware of general system problems.

When the technology has a restricted application, real problems are not so easily identified. The risk that random research will yield results that are inadequate to solve any specific problem exceeds the risk of duplicating effort, and it is suspected that the work is frequently of less interest to the performers of general scientific and engineering research. In order to gain a high payoff of restricted technological research, planning responsibility must be decentralized and assigned to the specifically interested applications-oriented system designers.

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# 7. REQUISITE LEVEL OF INVESTMENT IN RESEARCH

## 7.1 Strategy and Funding

7.1.1 Research Strategies: Every organization, whether it be a small company, a large corporation, a nation, or a national agency such as the Department of Defense, has a research strategy. It may be explicit and well documented, or it may be determinable only through induction based on observation of behavioral patterns. Nevertheless, the strategy exists and, more than any other single factor, defines the requisite level of investment in research for that organization.

At one extreme, research strategy can call for assuming a "parasitic" posture. In that case, the organization allows others to sponsor and conduct research; then it adopts (or adapts) certain of the findings in accordance with its needs and purposes. The cost of this attitude is measured in terms of patent fees and licenses—and, perhaps, in loss of competitive position. Such a research strategy is typical of many small companies and also of newly developing nations. As reported by A. H. Rubenstein,[28] it typifies most of the home-entertainment electronics industry in the Chicago area.

Further along in the spectrum is the strategy of "reaction," in which resources are allocated for research only to solve immediate problems. Great scientific discoveries are unlikely either to be made or, if encountered serendipitously, to be exploited. Radical technological innovations are neither sought nor expected. This conservative strategy seems to be acceptable to most consumer-products industry in the United States as well as in some of the smaller European nations. Expenditures can be modest and research efforts, highly selective. Appropriations need only be made after a problem has been identified. There may be additional expenses for licenses or patents, but the probability is somewhat less than in the case of the fully parasitic posture.

The reaction strategy, if tied to a well-planned, long-range engineering development program, does not necessarily incur any great risk of loss in competitive position, national or corporate. If observed too rigorously, however (as discussed later), it mitigates against the introduction of markedly new technologies and so leads to rapid increases in the cost of advanced engineering development.

The antithesis of the parasitic posture is an aggressive, forward-looking strategy. Clearly the most costly in terms of immediate cash layout, this strategy prescribes that scientific and technological

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[28]A.H. Rubenstein and D.E. Brewer, *Research and Development in the Chicago Area Electronics Industry* (Evanston, Illinois: Northwestern University, 1962).

opportunities be aggressively sought and, when found, exploited as considered necessary or desirable. In principle, this strategy avoids the risk of losing competitive position and minimizes the need for costly licensing arrangements. Its great disadvantage is that many findings will never serve a useful purpose, because they lead either to undesired capabilities or duplicative techniques, of which only the more attractive alternative will be useful. In practice, the forward-looking strategy in its ultimate form will probably never be adopted, because undoubtedly opportunities for research will always exceed ability to support the required programs.

7.1.2 Strategy for the Department of Defense: The fundamental concept that the DoD should support some research in both science and technology is not currently in question. It is generally recognized that a potential enemy who is technologically advanced (or advancing) represents an increasingly severe threat, and that consequently this nation's military capability must be continuously upgraded merely to maintain parity.

The *rate* of the DoD's investment in research, however, has been questioned. Competent authority suggests that "The high level of support of basic work is producing scientific and technical information at such a high rate that it cannot be effectively digested, interpreted, disseminated, or put to useful purpose." Translated into terms of the three strategies discussed here, it is agreed that the DoD must adopt a strategy of at least reaction, but it is felt that moves toward an aggressive, forward-looking strategy will require a more pragmatic rationale than has previously been afforded. This is inferred from the fact that critics are demanding greater proof of value in relation to the current level of expenditures.

In reality, the problem faced by Defense R&D management is twofold: First, define a research strategy that is consistent with the strategy employed in relation to all R&D; and, second, demonstrate that the research strategy defined is a sound one. The requisite level of investment in Defense research, then, will be the minimum needed to support that strategy.

7.1.3 Relevance of HINDSIGHT Findings to DoD Research Strategy and Funding: Project HINDSIGHT was neither intended to define a research strategy for the Department of Defense nor designed to defend whatever strategy has been used. Clearly, however, many of this study's findings are relevant to those matters. Further, the HINDSIGHT data permit a limited evaluation of balance among the several areas of technology in the DoD's research program.

The purpose of this discussion is to highlight those findings that bear on matters of research strategy and funding, interpreting the data where possible, or, where the data alone are inadequate to support a

conclusion, speculating on their probable significance. The logic is as follows:

(1) Consider the return on investment resulting from the strategy that has been espoused by the Department of Defense since 1945;

(2) Compare the DoD's research strategy with an averaged strategy of the intensively technological U.S. industries; and

(3) Examine the likely consequences of major shifts in DoD research strategy or funding.

## 7.2 Measuring Return on Investment

During the period 1945-1963, the Department of Defense spent approximately $10 billion on scientific and technical investigations. (This does not include a considerably larger sum that was invested in the engineering development of weapon systems and other military equipment.) The strategy adopted for the support of this research program can be inferred from several observations in Project HINDSIGHT.

The most significant relevant finding of this study is the determination that 67 percent of the RXD Events affecting the systems examined occurred prior to the designing of the equipment through which the Event was identified. That is, at most, one-third of the work could have been undertaken in response to specific problems uncovered while the system was being designed or developed.

This plainly suggests that a considerable portion of the research money was in fact invested under a forward-looking strategy. Supporting evidence is found in the definition of the R&D budget's six elements. Although this budget structure was not formally introduced until toward the end of the period studied, it served more to dignify existing practice than to impose a different research strategy.

Moreover, according to the historical funding pattern, from 20 to 25 percent of the R&D budget has been allowed for scientific and technical investigations. Any measure of the return to the nation from the Department of Defense's 1945-1963 investment of the $10 billion in scientific investigations inherently includes the measure of a forward-looking research strategy.

A crude but useful way to measure return on investment is by establishing the cost differential between a modern weapon system and an operationally equivalent array of its predecessors. This differential is then compared with the cost of the science and technology that enabled the advanced system. The posit is that the point of marginal return has been reached when the cost of new research exceeds the savings gained by replacing the earlier systems.

Essential to this analysis is the assumption that the [illegible] capability of the [illegible] [illegible] adequate to afford the [illegible] [illegible] defense. If the capabilities of modern weapon systems are [illegible] significantly in excess of the need, an adequate defense might have been provided by the older technology and this entire analysis is [illegible] meaningless. In view of strenuous efforts of the DoD toward cost consciousness, the assumption appears to be reasonable.

In addition to the difficulty avoided by the foregoing assumption, three other significant limitations of this approach to measuring return on investment must be overcome.

*First*, with few exceptions, the performance of a modern weapon system exceeds every essential function of its predecessor. [illegible] it is possible to establish the number of the older type that can be replaced by a single successor. Frequently, however, the successor system provides a completely new capability, one that no number of the older systems could match. For example, it is meaningless to compare any number of the 90mm or 120mm medium or heavy antiaircraft batteries of [illegible] 1945 with the more recent NIKE-HERCULES missile defense. The guns were so limited with respect to altitude that an infinite number of batteries could not afford equivalency. For purposes of the return-on-investment analyses, the systems are compared only on the basis of capabilities that both possess; excess capability on the part of the successor is treated as a bonus.

*Second*, because it is essentially impossible to identify and isolate the supported research in science or technology that contributed solely and totally to any given weapon system, a cost-value analysis of research in relation to a single system cannot be performed. It is possible, though, to estimate the total DoD investment in research during the time the knowledge was gained that enabled the system's development and, then, to consider any cost advantage of the new weapon system in terms of a percentage of the total investment.

The Task I studies of Project HINDSIGHT have demonstrated that the new knowledge utilized in modern weapon systems was gained predominantly during the years 1945 through 1963. DoD expenditures for research in science and technology in that period have been estimated as between $7.5 and $10 billion; the spread is caused by changes in accounting procedures that are believed to have obscured some of the expenditures. Hereafter, in comparing the savings accruing from each new type of system, the higher figure will be used.

*Third*, a difficulty arises as a result of various design compromises that have been made in a succession of weapon systems. This forces a certain amount of normalization of system designs before a comparison can be made. The fact that the requirement for a considerable amount of new technology continues throughout the engineering development of an advanced weapon system indicates that the system engineer has

[illegible] all the [illegible] available [illegible] new weapon system [illegible] available technology. [illegible] the absolute performance of the [illegible] with that of an updated version. [illegible] studied during Project HINDSIGHT.

[illegible] A representative example (particularly useful because the comparison does not involve classified information) is found in the A and E versions of the C-130 and the C-141 transport aircraft.

The C-130A incorporates the best pertinent technology available in 1954. The C-130E's performance demonstrates the increases that were enabled by new technological information accumulated between 1954 and 1962 - limited, however, by the designers' ability to retrofit the new technology to the older basic airframe and engine. The C-141's performance shows that comparatively much greater gains are possible through a totally new development program that can exploit all of the newly available technology. Comparative performance capabilities of these aircraft are shown in Figures 17 and 18.

In 1959, the Air Force introduced the C-130 transport aircraft into service; in 1964, the C-141 aircraft was added to the operating inventory. Project HINDSIGHT teams investigated the difference in the technologies underlying the development of these two aircraft and established that the performance characteristics of the C-141 could not have been achieved with the technology available in 1959. Through retrofit, the E model (an upgraded C-130) made use of technological knowledge acquired during the 9-year life of the basic aircraft design. Modification by retrofit imposes significant limitations on upgrading, such as the extent to which a fuselage can be stretched or engine power added without completely redesigning the aircraft. Despite those limitations, the productivity of the C-130 was increased about 40 percent, and the range, about 60 percent.

Where an entirely new design was undertaken, as for the C-141, the full potential of technology could be exploited. As a consequence, a payload differential in excess of 100 percent and an effective range increase of the same order of magnitude were achieved. In addition, the C-141's 1.6x combat speed advantage means that it takes fewer operating hours to deliver a payload over a given distance, and this, in turn, reduces overall operating costs. A very conservative estimate of the return on investment in scientific and technological research incorporated in the C-141 aircraft may be based on the relative operating costs per ton-mile capability of the C-141 and the upgraded C-130 over a 30,000-hour flight life.

Considering direct operating cost, system support, flight-crew pay and allowances, and depreciation, the total cost per ton-mile capability of the C-141 is estimated at $0.147. A similarly adjudged cost for the

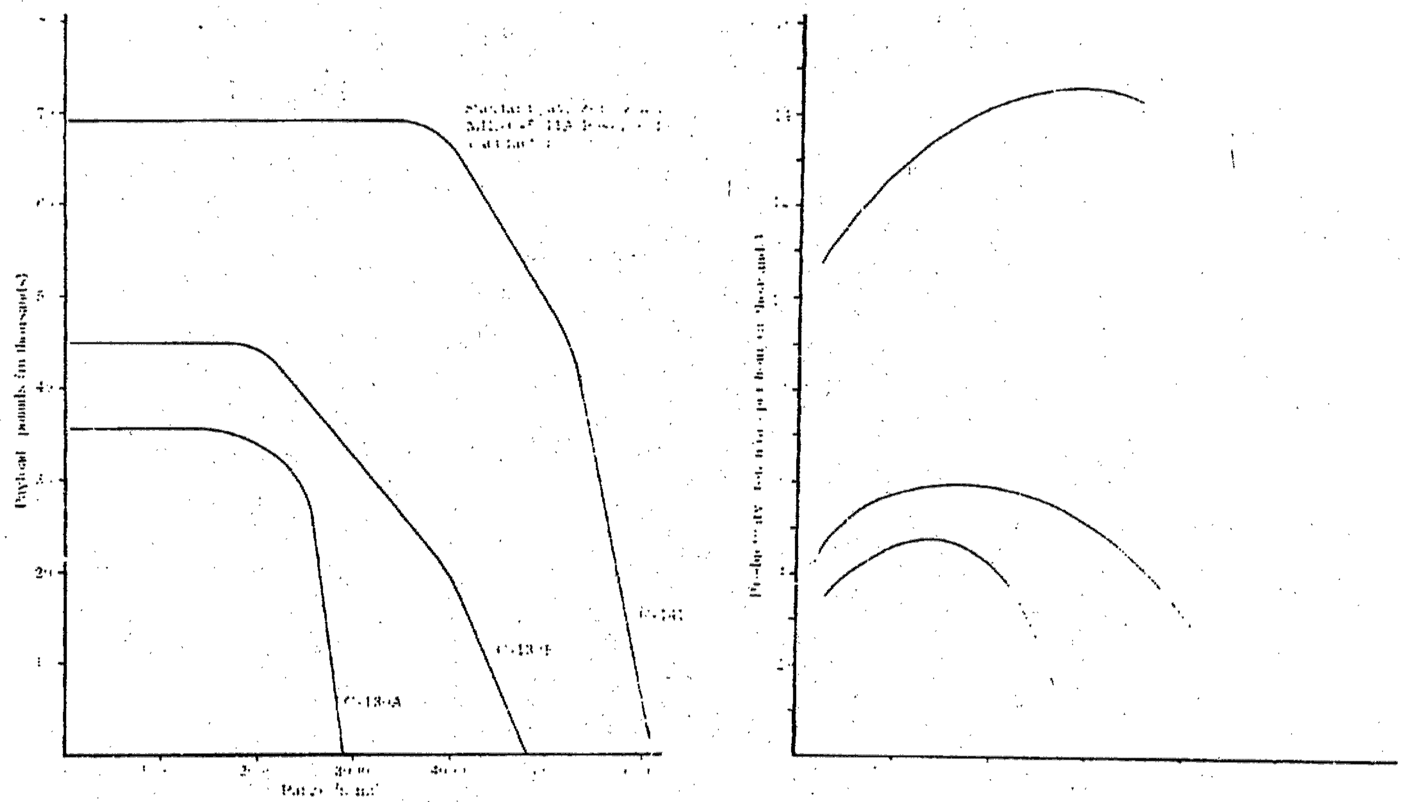


Figure 17. Payload Range Capability of C-141 Aircraft

[illegible] 50 18%, or an increase of [illegible] an 85 percent [illegible] factor over the life of the aircraft and [illegible] of 14,000 ton-nautical miles per hour, each C-141 offers [illegible] 30,000 x 36 x 10,000, or [illegible]. The 284 C-141 [illegible] or being procured offer a potential saving of $2.5[illegible] billion equivalent to over 25 percent of the total DoD investment in all research in science and technology between 1945 and 1960.

To clarify the comparison of the C-130 and C-141 aircraft, one point must be made. It is clearly understood that the mission-oriented design characteristics of the two aircraft differ. Given the technological capability to build both of the aircraft, the Air Force is in a position to build some of each type of aircraft, where such a choice better serves the total mission responsibility by optimizing the design for the mission. In the absence of technology permitting the C-141, however, there would be no option, and the C-130's characteristics would establish the limits on capability. It cannot then be concluded that additional savings would be realized by replacing all C-130s with C-141s. It can only be concluded that, in the absence of the C-141, the total mission would be more expensive because the C-130 (or its technological equivalent) would have to perform both the mission for which it is optimized and that for which the C-141 is designed.

*(U) SP and AN/SPS-48 Radars:* Another weapon system studied under Project HINDSIGHT was the AN/SPS-48 radar. This surveillance and target-acquisition radar, now being used in the fleet, is generally an operational successor to the SP surveillance radar of World War II. There have been other intervening radars, but in terms of technology all were subsequent to the SP. It may be assumed, however, that they used part of the new technology purchased with that same $10 billion, so they need not be considered in this analysis.

At least 40 SPs would be required to afford the same degree of effectiveness in radar surveillance as that obtainable from a single AN/SPS-48. Because of significant differences in the two radars' maximum range capabilities, 39 of the 40 SPs would have to be carried on separate ships, optimally distributed over a large area, to normalize space power density and data rates over the volumetric coverage of the AN/SPS-48. Let us assume that this could be done and that adequate communications could be arranged to maintain the distribution and enable the effective transfer of information.

The acquisition cost of the 40 SP radars would be from $6.5 million to $10 million more than the single AN/SPS-48, depending upon how much the unit cost might be reduced in view of the greater SP production. More important, though, 39 additional ships would be required, each with a total operating crew of some 200 and costing in excess of $15 million. Assuming costs of $200,000 per SP and $1.5 million per AN/SPS-48, the direct capital-expenditure cost of accomplishing, with 1945 technology

[illegible] at least

[illegible] million [illegible]

[illegible] million [illegible]

[illegible] million

To replace the 25 AN/SPS-48s under procurement would require

25 x $591 million = $14.8 billion,

or half again as much as the total investment in all the DoD supported research since 1945.

To a marked extent, the preceding example is specious. Had there not been advancing technology all across the spectrum, the aircraft threat that establishes the requirement for the AN/SPS-48 would not exist. The capability of the older radar might well have remained quite adequate. The sole intent in presenting this radar example was to enable visualizing the magnitude of the payoff of research in science and technology. The earlier example of the aircraft, on the other hand, is a more concrete, real-world case.

*(2) Other Systems:* The return on investment in research can be similarly demonstrated for each of the systems studied. To do so (particularly for expendable items such as missiles, mines, torpedoes or other munitions) would involve the use of highly classified information on expenditure-rate planning. In some cases (e.g., nuclear warheads), even relative-effectiveness ratios are classified. An indication of realized returns from new science and technology in some other systems, however, is suggested by the ratios shown in Table XXVIII.

Table XXVIII. TYPICAL INCREASES IN RATIOS OF OPERATIONAL-EFFECTIVENESS IMPROVEMENT ENABLED BY TECHNOLOGY

| Weapon System: Current | Weapon System: Predecessor | Estimated factor of operational improvement in a common role |
|---|---|---|
| M-102 105mm Howitzer | M2A1 105mm Howitzer | 1.4 |
| Mk 46 Mod 0 Torpedo | Mk 44 Torpedo | 32.0 |
| Mk 56 Mine | Mk 10 Mine | 10.0 |
| BULLPUP ASM | Free-Fall Bomb | 4.0 |

[illegible] the enhanced capabilities and the cost savings which [illegible] through these new systems can be considered attributable to the $10 billion DoD investment in science and technology. Now, if the cost savings calculated for the aircraft and radar system examples are at all typical of the many equipment types in the roughly $80 billion Defense inventory, that $10 billion has been repaid many times. It appears unlikely that the point of marginal returns has been reached.

### 7.3 Program Balance

Despite the demonstration that investment in scientific and technological research has offered a considerable economic return, it can still be charged that better management might have resulted in equal returns from a smaller investment. One very meaningful test of the adequacy of management is offered by the HINDSIGHT data.

Undoubtedly the two most difficult decisions that must be made by managers of the DoD research program involve the total number of dollars to be made available for research each year and the relative apportionment of funds among the competing sciences and technologies. This study does not extend to a direct test of the wisdom reflected in total dollar levels. It is possible, however, to estimate the quality of judgment exercised in apportionments. One might then speculate that, because the same people were involved in both sets of judgments, the wisdom displayed was about as good in one as it was in the other. Also, an indirect test of the reasonability of the total dollar level is presented in section 7.4.

In Table XXIX, many of the sciences and technologies shown in Table VIII are listed in relative order of funding during FY 1966. Some items were omitted because the systems in which those technologies would be important were not represented by the types studied in Project HINDSIGHT.

Table XXIX. RELATIVE FUNDING OF SCIENCES AND TECHNOLOGIES, FY 1966

| | |
|---|---|
| 1. Missiles | 8. Physics |
| 2. Navigation and communications | 9. Mechanical and civil engineering |
| 3. Ordnance | 10. Materials |
| 4. Electronics | 11. Mathematics |
| 5. Propellants and fuels | 12. Chemistry |
| 6. [illegible] | 13. Atmospherics |
| 7. [illegible] and equipment | 14. Energy conversion |

[illegible] rank correlation between table [illegible] results in a coefficient of [illegible] would be considered [illegible] "high" correlation [illegible] increases in funding for electronics and material [illegible] navigation and communications would raise the [illegible]

It is noted that, among the R&D events funded, [illegible] oriented to Defense needs, electronics and materials science [illegible]. That is, the managers of DoD's research programs could rely on [illegible] industry for some of the requisite new knowledge in these areas. [illegible]ly, the DoD should have allocated less support to R&D in electronics and materials.

With regard to the apparently overfunded navigation and communications technologies, several factors must be considered. First, the only system studied that relied on those technologies was the Navigation Satellite, and only the orbiting portion of the system was examined. Next, major advances in those technological areas postdated most of the time frame (1945-1963) with which Project HINDSIGHT is concerned. Thus, although for differing reasons, the HINDSIGHT data do not afford an especially good test in the case of electronics, materials, navigation or communications.

It is possible that this particular coefficient of rank correlation measures a circuitously self-serving phenomenon; that is, as a consequence of heavy funding, there have been more accomplishments in certain areas of science and technology. Undoubtedly there must be some correlation between level of funding and probability of successful achievement; to some degree, there is a resultant bias in the HINDSIGHT data. In general, however, the approach used in this study—the retrospective tracking of the flow of science and technology, starting with utilized rather than laboratory-advertised products of research—serves to minimize the consequences of the bias.

To the extent that managers of DoD research dictated the nature of the weapon systems to be developed, they had opportunity to encourage the use of their programs' results in those systems. Wherever the weapon system was developed by an independent agency, such as an industrial contractor, the opportunity would be minimum; and that was the situation with respect to almost all the weapon systems studied in Project HINDSIGHT. Thus, the rank correlation does measure the quality of managerial judgment in at least the matter of resource allocation.

As previously noted, a coefficient of rank correlation of 0.7 would be "high." Ignoring the possibility of logical adjustment to 0.93 as described before, a correlation of 0.83 is enough to demonstrate that management has done an excellent job of allocating its resources among competing scientific disciplines and areas of technology.

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[3]Correlation significance test: t = 5.15.

[illegible]

[illegible] research funding and permit the selective use of other [illegible] [illegible]. Specifically, they demonstrate that the Department of [illegible] [illegible] at a very high level ([illegible] to 96 percent) upon its [illegible] [illegible] to produce the technical information it [illegible].

In addition, the HINDSIGHT data show that the DoD [illegible] forward-looking research strategy (as discussed in section 7.5 and [illegible]) in the [illegible]. The strategy and importance of the Defense research program having been described, it is possible to find analogous [illegible] in other research sponsoring organizations and then to estimate what the funding level would be if the DoD were to adopt the research strategies of those other organizations.

Certain segments of U.S. industry, either voluntarily or (more likely) in response to the threat of competition in a free market, have adopted a forward-looking research strategy. The aerospace, computer, pharmaceutical, petrochemical and other similar businesses represent the technologically intensive segment of the nation's industry. Some entrants into those fields have succeeded and grown; others have failed and disappeared. It is reasonable to postulate that research strategy, including its funding aspect, has been a significant factor in the success or failure of individual companies. In any case, it is difficult to challenge the wisdom of strategies employed by commercially successful companies.

In general, companies that are deeply involved in technological activities must maintain aggressive research and development programs; the marketplace holds a continuing challenge. The Department of Defense is in a truly analogous situation only when international peace is in serious danger. When there is no immediate threat to national security, it may be possible to curtail or postpone the development of new weapon systems until, as technology grows, opportunities for even better weapons arise. If the DoD research program is maintained at a healthy level during those relatively peaceful times, the balance between research and development should shift away from that adopted by industry. In brief, *[illegible] imminent danger to the national security, the [illegible] development undertaken by the Department of [illegible] be at least as great as that of technologically intensive [illegible].*

During the past few decades the national security has continuously been in jeopardy. The allocation of DoD resources between research and development can be meaningfully compared with that of this industrial sector.

[illegible]

[illegible] analysis of the two sets of definitions suggests that about [illegible] of research in the DoD research category corresponds with the NSF category of basic research, 25 percent of the DoD's research, all of the exploratory development, and a portion of [illegible] management and support corresponds to the NSF's category of applied research.

On an average, for the 5 years from 1962 through 1966, DoD effort reported as applied research ran about 1.4 times greater than those reported as exploratory development. Thus, the 4 percent and the 19 percent for basic and applied research, respectively, translate to 6 percent of the total R&D budget for research and slightly over 14 percent for exploratory development.

Utilizing DoD strategy as a base for calculation, Table XXX displays, for fiscal years 1962 through 1967:

. the reported DoD apportionment for total R&D (column 2);

. the approxim[illegible]penditures or allocations for research and exploratory developme[illegible]olumns 3 and 6);

. the levels that would have been assigned if the average industrial funding strategy had been invoked (columns 4 and 7); and

. the percentage differences (columns 5 and 8).

Apparently the Department of Defense has adopted a more conservative posture than industry with respect to research and, until recently, a more aggressive posture concerning exploratory development.

Difficulties in reconciling the two sets of definitions may be responsible for greater apparent differences in this table than actually exist—that is, the DoD's definition of research may be more rigorous than industry's. The consequence of that difference would be a misleadingly high industrial figure for research strategy (column 4) and a correspondingly low figure for exploratory development (column 7).

[3]*Reviews of Data on Science Resources* (Washington, D.C.: National Science Foundation, NSF 66-33, December 1966), p. 9.

[4]*Basic Research, Applied Research, and Development in Industry, 1964* (Washington, D.C.: National Science Foundation, NSF 66-28, June 1966). *Federal Funds for Research, Development and Other Scientific Activities, FY 1965, 1966, 1967* (Washington, D.C.: National Science Foundation, NSF 66-25, 1966), 15.

| | | [illegible] Strategy | | | Exploratory Development Strategy | | |
|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | DoD | Industry | Diff. | DoD | Industry | Diff. |
| [illegible] | $[illegible] | $340 | $[illegible] | 20 | $[illegible] | $[illegible] | [illegible] |
| [illegible] | [illegible] | 35[illegible] | [illegible] | [illegible] | 1,09[illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | 35[illegible] | 4[illegible] | 2[illegible] | 1,130 | [illegible] | 1[illegible] |
| [illegible] | [illegible] | 38[illegible] | 42[illegible] | 10 | 1,16[illegible] | 9[illegible] | [illegible] |
| [illegible] | [illegible],600 | 390 | 456 | 17 | 1,131 | 98[illegible] | [illegible] |
| [illegible] | [illegible] | 414 | 47[illegible] | 14 | 1,040 | 1,020 | [illegible] |

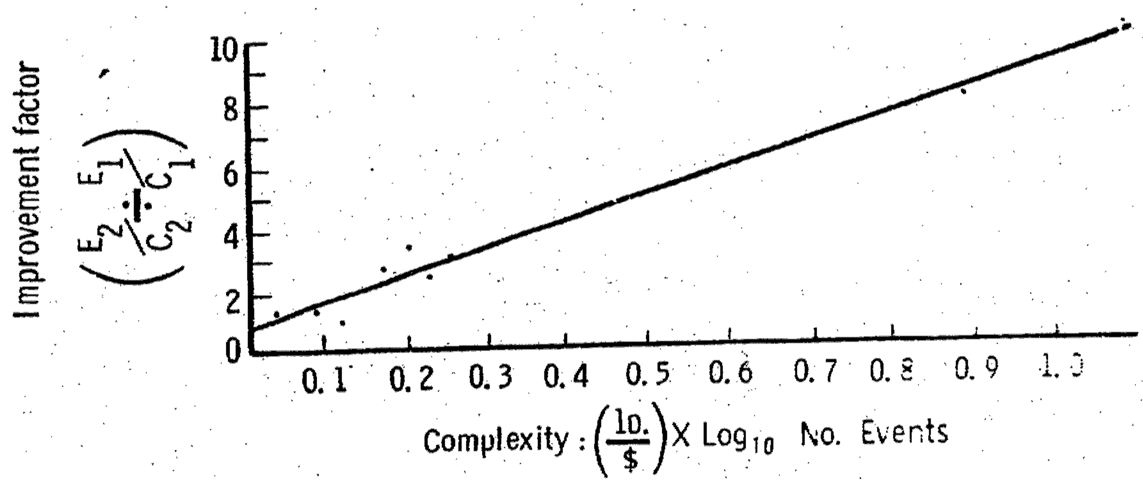
A comparison of DoD and industrial totals for research and exploratory development combined suggests that the DoD's investment in R&D has varied from what the average industrial strategy would dictate by a difference ranging from a high of 13.6 percent to a low of -2.6 percent.

Obviously, the analogy between the Department of Defense and industry is not good enough to permit using this analysis for more than a rough check. Compressed time schedules for weapon-systems development, higher development costs resulting from system specifications for extreme degrees of maintainability and reliability, and the like, combine to create a situation in which the DoD's apportionment would be shifted somewhat closer to development than is necessary in industry. This shift should be partly offset by the fact that it is more important to ensure the survival of the nation than of a single company; and, therefore, the DoD should adopt an even more forward-looking research strategy than the most technologically intensive industry. Nevertheless, the analysis does demonstrate that the level of DoD expenditures for research in science and technology has not been significantly out of line with what U.S. industrial strategy would prescribe in an analogous environment.

## 7.5 Economies of a Forward-Looking Research Strategy

In the preceding section, it was noted that the Department of Defense evidences a forward-looking research strategy and further (without demonstration) that such a strategy can be the most effective and efficient of the several possible alternatives described in section 7.1. Findings of the HINDSIGHT study suggest that, if a steady increase in weapon systems' performance or cost-effectiveness is sought, the only way to avoid a rapid escalation of research cost is to adopt an aggressive, forward-looking research strategy calling for a considerable amount of highly speculative research.

Figure 19. RELATIONSHIP BETWEEN IMPROVEMENT, COMPLEXITY AND REQUIREMENT FOR NEW TECHNOLOGY



[illegible] 10 of the 20 systems studied by the Project, there are reasonably well defined predecessors. It can be said, as a generalization, that in these 10 cases the technological differences that were responsible for improving the systems' cost effectiveness and operational efficiency could be found in the improved capabilities of functionally similar components and materials. These are the improvements that can be expected to result from a strategy of reaction. As a component's deficiencies are identified, a research program can be undertaken to improve the component without necessarily seeking radical new techniques for performing its function. Again, this is a generalization, but it is far more often true of the 10 systems than not.

In Figure 19, the estimated improvement factor for the predecessor-successor pairs is plotted against a measure of the predecessor's technical sophistication as a function of the number of RXD Events required to attain the more advanced successor system. "Improvement factor" is defined as the ratio of the successor's cost-effectiveness to that of the predecessor. (More rigorously construed, it is effectiveness/cost: effectiveness/cost.) The sophistication of the predecessor is assessed in terms of cost per pound of the production model. The particular function of the number of RXD Events is the logarithm to the base 10 of the number.

Intuitively, the mathematical formulation expressed in the plot appears reasonable. Experience tells us that generally, as an equipment becomes more complex or sophisticated, a greater amount of effort is required for each successive increment of improvement. Analytically, that experience may be rephrased: The improvement factor is proportional to some nonlinear function of the added complexity or sophistication of the new system and to the level of complexity or sophistication of its predecessor.

For the first-order approximations permitted by the available data, it appeared reasonable to assume a logarithmic relationship between number of RXD Events and improvement factor. (The reasonability of this assumption is supported by the fact that the data fit a straight line over a range of departure that exceeds a factor of 10 on the vertical axis and a factor of 30 on the horizontal.)

Figure 19 provides a means of speculatively demonstrating the level of research costs that might be expected if the Department of Defense were to employ solely the strategy of reaction in its research activities. Assume, for example, that an improvement factor of about 60 percent is desired in a solid-propellant, inertially guided ICBM. From Figure 19, the factor, "complexity X $\log_{10}$ No. RXD Events," is seen to be 0.07. Knowing that an ICBM of the current generation delivers for roughly \$40 a pound, a requirement for close to 1,000 scientific or technological advances is evidenced. Now let us assume (very conservatively) that, on the average, we can expect full success in 25 percent of our research program. That is, of every four ideas tested, at least one will be found worth pursuing.

[illegible] ated in section 5.5.5, the [illegible] to [illegible] idea, i.e., demonstrate its feasibility, [illegible] additional cost of about 15 times that much was required to carry the idea to the point of practicality. On that basis, [illegible] 4,000 ideas and [illegible] for each of 1,000 demonstrated, feasible [illegible], an estimated total of $850 million would be required for research in science and technology to achieve an improvement factor that in all probability would not be great enough to gain acceptance for the [illegible] advanced ICBM.

If the researchers were asked to provide a means for improving a military capability rather than improve a given type of system, the ensuing situation might be completely different. To demonstrate what might occur, based on experience, let us look at a different example. Operationally, the Starlight Scope, a night-vision device studied in Project HINDSIGHT, replaces the 7x50 binoculars. Obviously, it is most unlikely that any amount of improvement in the optics or mechanical structure of binoculars could match the new device's light amplification capability. Nonetheless, assume that, instead of introducing completely new techniques based on results of some speculative research, it was desired to improve the binoculars.

Working through Figure 19 and using the actual improvement factor (which is classified) of the Starlight Scope over the binoculars, one finds that, again, about 1,000 RXD Events would be needed, as compared to the less than 30 Events that were actually identified by the study team.

Another example offering comparable numbers is the Navigation Satellite with a "much improved" loran radio navigation system.

Admittedly, both examples are specious; but they do make the point that marked operational improvements in sophisticated equipment are far more likely to be achieved at moderate cost when completely new techniques are introduced than when the overall improvement is sought through the deliberate refinement of each technique used in the predecessor equipment.

These simple cases should demonstrate beyond any reasonable doubt that an aggressive, forward-looking research strategy with considerable room for speculative research is essential if weapon systems are to be improved on the basis of new science and technology gained at minimum cost.

[illegible]

[illegible]

[illegible]

(c) Would a 10 or 20 percent reduction in the annual [illegible] still bring an acceptable return?

5.6.1 Payoff of Doubled Investment: Detailed studies of each weapon system that was significantly improved (by a factor of 1.5 or more) over a predecessor system that performed a generally similar military function reveal a common pattern. It is relatively easy to identify on the order of 100 to 200 scientific or technological advances that contribute to the improved performance of the later system. Typically, the potential consequence of any single Event is trivial. It is, rather, the skillful integration of many advances that gives the new system its greater operational capability.

A number of the advances—usually in technology and typically about half of those identified through a single system study—are not obviously contingent upon any other recent advance. The relevant science is old; the materials and fabrication techniques required to implement the idea in a useful form have been available for some time. Apparently independent of anything else, these advances could occur at any time; and undoubtedly the frequency of their occurrence could be accelerated by the infusion of more money into R&D programs.

The other half of the Events, however, are clearly dependent on other recent advances in science or technology, very often (as noted in section 5.1.1), on new materials.

It is the latter group of scientific and technological advances that provides the pacesetters. Because they must be sequential in time (each conceived, its validity tested and demonstrated, and its existence advertised before it can be used), it is not obvious that increased funding will significantly hasten the realization of advanced weapon systems.

Moreover, to the extent that current management may be less than optimum, there may be unnecessary delays in making resources available for testing ideas or in advertising new scientific or technological capabilities. This, however, involves the management of available funds: it doesn't provide an argument for additional funds or indicate that additional funds would offer any particular advantage.

Next, as noted in the findings (section 4), a significant number of RXD Events occur during systems development and respond to problems that

arise during that time. It cannot be assumed that early, [illegible] serendipitous solutions to any great number of these [illegible] problems would be reached solely as a consequence of an increase [illegible] of funding for research.

Finally, it must be recognized that the payoff of technological research is in the system that is eventually developed, not in the technology itself. Accelerated technological growth is profitable only when accompanied by a readiness to undertake engineering development of the equipment that will use the new technology. Once the realized weapon systems satisfy operational requirements, the point of marginal return on investment in systems development—and concomitantly on investment in scientific and technological research—has been reached.

In brief, the criterion for the research program's size is based on the needs of future weapon systems and other military equipment, which in turn are defined by future operational requirements. In the absence of identified future operational requirements that can be interpreted as a need for doubling the research budget, little gain can be expected from such an action.

7.6.2 Acceptability of Reduced Investment: The answer to the second question, "Would a 10- or 20-percent decrease in the annual investment still bring an acceptable return?" depends upon intentions regarding future system developments. Assuming that the replacement of weapon systems will continue on a roughly 10- to 15-year time scale, as noted in the system studies, the data suggest that any decrease would be unwise.

First, it is to be expected that a reasonable percentage of the replacements will be markedly upgraded versions of the same systems. Figure 19 demonstrates that, for these cases, the research budget should be greater than it was in the 1958-1963 period, in which about half of the new technology used in the systems examined was spawned.

Next, as Figure 14 shows, 33 percent of the requisite new science and technology was generated after the using system entered engineering development. The need for many of those RXD Events could not reasonably have been anticipated before system design began. A considerable portion, however (perhaps 20 to 30 percent as a rough estimate), could have been foreseen and the necessary research undertaken if the funds had been available.

With the advent of advanced management systems[37] for procuring weapon-system development and the requirement for detailed contract definition—along with insistence upon the use of fixed-price development contracts and the introduction of incentive contracts calling for

[37] M. Meyerson, "Price of Admission into the Defense Business," *Harvard Business Review*, 45, 4, 1967.

penalties as well as rewards. It became clear that the technical risk in systems development will be reduced. This can be done only by resorting to ultraconservative design practices. Before new technology can be incorporated into system designs, therefore, its worth will have to be proved. With this in view, it is far more likely that modest increases in the research budget will be warranted than reductions permitted.

### 7. Cost Effectiveness Controls in Research Management

It has been suggested that improved management of the DoD's research programs could reduce costs by establishing cost effectiveness controls at a senior level in the decision process. Two findings of Project HINDSIGHT question the practicability, the feasibility, and even the desirability of such a concept.

The first and perhaps more important of the two findings is that, surprisingly often, a particular set of circumstances was found to exist when a really new idea was introduced. In each case, the judgment of recognized authority was that the research proposal offered less promise than another, more popular one. The situation was sufficiently aggravated that the less renowned individual found it necessary to establish separate laboratory facilities and seek new sources of funding to pursue his ideas. Interestingly, in at least four examples found during Project HINDSIGHT, the new idea eventually resulted in a dominant technology. If reasonable cost-effectiveness criteria had been enforced, it is likely that those new technologies would not have become available.

In retrospect, the difficulty of fairly appraising a new science or an untried technology is apparent. The basis for judging either cost or effectiveness in those cases—to the extent that the situations can be reconstructed—would not have been adequate to warrant supporting the research.

Multisource funding is essential to the continuing encouragement of new ideas and the maintenance of viable technology. This situation is not compatible with detailed cost-effectiveness previews at senior management levels. Clearly, in view of the magnitude of the research efforts discussed here, discretionary expenditures by laboratory-level management are essential.

The second pertinent matter suggested by the HINDSIGHT data concerns the typical amount of time that elapses between an idea's conception and the beginning of actual research on it. The median delay appears to be a few days. The average delay was 3 to 4 weeks, a few very extensive delays accounting for the big difference between mean and median times.

On the basis that this was only a sampling of Events, the tentative conclusion is that the processes of research in science and technology are generally intolerant of extended delay. Presumably, unless resources are quickly made available, the originator of the idea turns to other

[illegible] that it is impossible to [illegible] approaching [illegible] all the [illegible] [illegible] within a period of days.

It is not suggested that all controls [illegible] management [illegible] that the cost effectiveness procedures currently [illegible] by systems engineering management are inappropriate at [illegible] level, in the research community.

## 4.8 Relevance of HINDSIGHT Findings to Investment in Research

The finding that each succeeding generation of a weapon system requires more new science and more new technology suggests that, merely to maintain minimum acceptable increases in systems cost effectiveness, the future annual investment will continue to rise.

Several possibilities for a better management concept are offered by this study's findings, and their judicious employment should improve the funding and conduct of research. In general, this report's scope does not extend to the operational interpretation of the actual means by which management may be improved. Investment in research by the DoD has produced a high payoff in improved systems effectiveness through the combination of several factors. As stated in the finding (section 4.3.7): A high combined inventiveness, or ingenuity, and utilization rate are dependent upon the time and space coexistence of four primary factors— the recognition of need, a source of ideas in the form of an educated talent pool, capital resources, and an adequate communication path to potential users. The primary responsibility of the Department of Defense research managers is to find the means of ensuring the presence of all four in the proper balance to meet future systems needs.

## METHODOLOGICAL VALIDITY

The validity of Project HINDSIGHT's methodology is equal to that of the statistics of large numbers. This approach is based on the fact that the Department of Defense has spent many billions of dollars developing generations of operationally or functionally similar weapon systems, and the methodology should be equally useful to any agency or corporation with a similar history.

The analysis of information gathered by the HINDSIGHT methodology, however, leads to conclusions that are meaningful only in terms of each organization's mission. For example, an agency whose objective is the growth of educational institutions and an agency that is restricted to the use of research products would interpret "undirected basic research" differently.

Since Project HINDSIGHT began, these studies have been given a considerable amount of exposure to the U.S. scientific and technological community, chiefly through the publication of formal papers and inquiries by interested people. As a consequence, a number of questions have been raised and criticisms voiced about real or fancied weaknesses of the methodology. At the same time, participants in the studies have also been concerned with methodological validity. For that reason, the most obvious suspected weaknesses and those that could be most significant are analyzed here.

### 8.1 Difference in Investigators' Abilities

Even though a reasonably succinct definition of an RXD Event was established, the investigator with the greater sensitivity, experience, interest and diligence would identify more Events. He would also more readily appreciate that there may be several Events in a scientific or technological advance that a coworker might consider represents only a single Event. This methodological weakness was circumvented to some extent by using teams of 5, 10 or 20 investigators on a single system, and this provided an averaging effect.

More important is the fact that the total study is relatively insensitive to the exact number of Events found in studying a given system. In cases where only one, two or three Events were identified, the value of new research findings to weapon systems might be suspect; or the evidence could be interpreted to mean that a very small but sharply focused research effort might suffice for the future. In the range of 20 to hundreds of Events, however, particularly where a great diversity of the utilized areas of a technological or scientific discipline is noted, the evidence clearly denies the potential of a limited research program.

To permit correlating the amount of new science or technology that was used and increases in the resultant cost effectiveness of the military systems studied, it is necessary to adjust the Event count per system to compensate for the relative thoroughness of the individual studies. But, again, the requisite precision of the number of Events identified need be no better than the precision with which cost effectiveness ratios are estimated.

To this end, the number of Events actually identified per system may be assigned a normalizing multiplier factor based upon the study team's estimate of the thoroughness of its coverage. (See section 4.1.2.) Thus, for the C-141 aircraft study, a multiplier of 5 may be used, with 1.33 for the LANCE missile, 1.05 for the Mark 56 mine, and so on.

## 8.2 The Experiment's Repeatability

A sampling of all RXD Events, rather than an exhaustive study, tends to mitigate against the expectancy of a high degree of experiment repeatability. That is, if a different team were to repeat the study of a system—particularly one like the C-141, in which the sample studied constituted about 20 percent of the Events identified—a different set of Events might be found. Conceivably, that could introduce marked differences in the distribution of factors discussed in section 4, "Principal Findings."

To measure the probability that different groups of technically competent investigators would identify significantly different Events as most important to a given system, two separate studies of the Mark 46 Torpedo were made. One team investigated almost 40 percent more Events than the other. Although the larger sample still contained less than an estimated 70 percent of the possible Events, it included approximately 90 percent of the Events studied by the other team.

More important, however, distributions among such matters as funding sources, research-performing agencies, Event costs, etc., were essentially the same. In retrospect, this is not surprising, for, without regard to the weapon systems studied, these distributions remained sensibly constant during the time the HINDSIGHT data base grew from 100 Events drawn from seven weapon systems to 710 Events from 20 systems.

## 8.3 Basis for Invention Claims

Another question on the study methodology concerned the teams' apparent willingness to accept claims for inventions in the absence of patents or other documentary evidence. In terms of the Project's objectives, this is not a weakness; and in some cases the investigators in fact doubted the absolute validity of claims. If the identified group was really not the original inventor but honestly thought it was, as long as management agreed with the performing group, the environment in which

[illegible] would have been a function of the perceptions [illegible]. The erroneous assumption of an investigator makes no difference.

Moreover, HINDSIGHT is concerned with the transfer of knowledge from research to application. Above all, the knowledge shown to have been used was either created or recreated by an identified performing group, which should be the focus of attention. In short, the Project is attempting to compile a history of the expanded usage of science and technology in advanced weapon systems, not a history of scientific and technological growth itself.

## 8.4 Period Covered by Studies

As discussed in section 6.2.4, "General Observations," the transfer of research events from undirected basic research to system application can require 20 years or more, as compared to about nine years for the directed basic research category. Since the focus of Project HINDSIGHT was on the post-1945 period, it is acknowledged that full recognition has not been given to the long-term growth of scientific knowledge. The reader is reminded that the strategy adopted in HINDSIGHT, as described in the Executive Summary, included determining to what extent performance (cost-effectiveness) of new weapon systems was dependent on recent advances in science and technology. Therefore, no valid conclusions can be drawn from HINDSIGHT concerning the long-term value of undirected basic research, since many of these important events fall outside the time frame of this study (1946-1963).

## 8.5 Investigation of Failures

Project HINDSIGHT's methodology might also be criticized because no control group has been established; but failures are extremely difficult to define, and failures or unutilized RXD Events have not been investigated.

For instance, although it never became operational, the NAVAHO missile was a most prolific source of useful technology. It appears, therefore, that profitable lessons regarding poor research management cannot be learned from a study of unsuccessful weapon systems. Research is undertaken in the quest for knowledge, and the disproof of one hypothesis may be just as important as the proof of another. Thus perhaps only inconclusive research may be classed as a failure. But the difficulty of discriminating between inconclusive and incomplete research is a delicate problem that is well beyond the scope of the teams identifying RXD Events.

[illegible] scientists in the [illegible] [illegible] [illegible] research effort [illegible] [illegible] [illegible] [illegible] organizations that were already identified as productive [illegible] study teams. Until more elaborate management studies are [illegible], the analysis of what appear to be significant management factors [illegible] relatively restricted.

For the time being, it is only possible to compare patterns [illegible] fied as successful with general policies as the analysts under [illegible] to illustrate, a very high correlation is observed between [illegible] funding and generation of new knowledge, yet current management policies tend toward the greater centralization of funding control.

Again, procurement policies relating to weapon-system development are based on the assumption that all the requisite technology is in hand and that essentially all technical problems can be discovered in the concept-formulation and contract-definition cycle. The evidence that 20 to 40 percent of the new knowledge is generated after the development contract is awarded invalidates that assumption.

More subtle conclusions must await completion of the second task.

8.0 <u>Bias of Investigators</u>

Despite the advantages of using senior in-house Defense personnel to identify RXD Events, there was concern over the possibility of bias on their part. As a consequence of their primary jobs, these people have a personal interest in the DoD laboratories and might be expected to picture their parent organizations in the best possible light. This undoubtedly tended to increase the number of Events identified as occurring in the DoD laboratories in ratio to those originating in the universities and industry.

A counterbalancing effect was noted and described, however, by some of the weapon-system study teams. In the words of the team captain on the MINUTEMAN II study:

> It must be realized . . . that industry is much more ready to answer government solicitations for reports of contributory research than even government labs or universities would be because of the profit motive. Industry was, in most cases, happy to supply our team with reports to show their research contributions to MINUTEMAN; whereas government labs had often changed personnel and did not have either the time, the historical records, or as great a motivation to show their remote and indirect contribution to MINUTEMAN. Industry's contribution was more directly applied and more easily and quickly obtained from records.

It is likely that, if any contributions were [illegible], they were the universities'. Yet the consequence of this bias is not [illegible], to favor the in-house laboratories. A comparison of the relative [illegible] of people involved in each Event, as a function of organizational type, indicates that the relative productivity of scientists and engineers (in decreasing order) is: university, industry, in-house laboratory. This finding is probably based on the fact that the investigators credited peripheral participants in the DoD laboratories more easily, or more readily, because of bias, than they did such people in the universities and industry.

The investigation itself responds primarily to hard work, patience and persuasion. Among the essential characteristics of the investigator are sensitivity—based on broad experience in research or exploratory development, system work and technical management—and a critical sense that demands supporting evidence and confirmation of information received. Purely technical experience in a single specialty does not suffice. To the greatest extent possible, these criteria were considered in selecting the members of study teams.

## 8.7 Distribution of Event Types

Probably the most serious drawback in this approach is an inherent bias in the types of technical accomplishment uncovered, an uneven distribution that can perhaps be eliminated only by asymptotically approaching completeness. Thus, during this type of study, a typical ordering may be as follows:

(1) Engineering achievements involving subsystems and major components. These were treated as "elements" or sources of the type of information sought.

(2) Specific creative activity in design engineering that has the effect of advancing the state of the art, is frequently patentable, and is essential to meeting specifications. Such activity has been included within the class of RXD Events in spite of its *ad hoc* character, since there seems to be no good reason for excluding it.

(3) Exploratory development in materials and materials processing, which is characteristically performed by industry.

(4) Other exploratory development, also predominantly industrial.

(5) Research performed in industrial or government laboratories in the United States or abroad that led directly to exploratory development.

(6) Research in universities leading to exploratory development.

(7) Research in the physical, engineering and environmental science leading to information that is frequently taken for granted but is essential to a system's synthesis as well as its performance in the real environment.

(8) Research in the mathematical and life sciences, also often taken for granted but vital to system design and operation.

As anticipated, categories 3, 4 and 5 accounted for most of the Events, although a disproportionate amount of attention was given to 6, 7 and 8 to compensate for the problems encountered in locating them.

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APPENDIX A

DIRECTOR OF DEFENSE RESEARCH AND ENGINEERING
WASHINGTON D.C. 20301

6 July 1965

MEMORANDUM FOR ASSISTANT SECRETARY OF THE ARMY (R&D)
ASSISTANT SECRETARY OF THE NAVY (R&D)
ASSISTANT SECRETARY OF THE AIR FORCE (R&D)

SUBJECT: Project HINDSIGHT Expanded Studies of Research and Technology Which Have Been Utilized in Weapon Systems

The pilot study performed with an ad hoc in-house group on the BULLPUP (ODDR&E, 15 December 1964) and the larger study performed under contract to Arthur D. Little, Inc. (1 June 1965), copies of which have been provided to your office, have shown the feasibility of a method of historical analysis which is based upon the identification in weapon systems of the most significant contributions from research and exploratory development (RXD events). These RXD events can be analyzed, as the two pilot studies illustrate, so as to identify management factors which appear to be associated with their utilization.

A broader data base than that provided by the pilot studies is needed to more firmly establish, or perhaps disprove, the hypotheses made thus far. In addition, a broader data base has the possibility of providing some sort of quantitative measure of the overall payoff to weapon systems of the Department of Defense investment in research and technology.

Finally, the report of the House Committee on Defense Appropriations (Report No. 528, 17 June 1965) has questioned both the efficiency of management and the overall payoff of the Defense Sciences part of the RDT&E budget.

I believe the time has come, therefore, to make on a priority basis a comprehensive analysis of the impact of research and technology on a substantial number of important weapon systems now in use, in procurement, or in the advanced stages of engineering development. This study will seek: (a) to identify and firmly establish management factors for research and technology programs which have been associated with the utilization of the results produced by these programs; (b) to measure the overall increase in cost-effectiveness in the current generation of weapon systems compared to their predecessors (when such can be identified) which is assignable to any part of the total DoD investment in research and technology. It is currently estimated that, counting all

types of direct and indirect support of [illegible] DoD investment since 1946 has been about 10 billion [illegible]

Due to the ultimate importance of the conclusions [illegible] to management policies, and especially due to the concern of [illegible] regarding the future of the Defense Science budget, I am initiating a project to be known as "HINDSIGHT." To carry out this project, I am establishing on a priority basis an in-house study group in the office of the Deputy Director (Research and Technology), with the assignment of making a comprehensive analysis of a substantial number of selected weapon systems, with the goal of at least a preliminary report by April 1, 1966. Each Military Department will be asked to provide full time experienced technical officers or civilian engineer scientists working according to the plan outlined in Attachment 1. The number will have to be determined as time goes by, but eventually up to 20 from each Department may be indicated.

By designating the participants as in house, I expect that the majority will be from DoD laboratories, and systems engineering and management organizations, although participation from the special nonprofit organizations will be encouraged in areas where their expertise is needed. We wish, however, to exclude contractor organizations specifically hired for this task. I believe the in-house and special nonprofit groups will do a better job than contractor organizations because (a) they have broad, relevant experience, (b) using the method of forming teams, people with specialized experience can be matched to particular systems, (c) they have more ready access to the necessary information, much of which may be proprietary, and (d) the educational value of participation will be substantial. The last point is particularly important since one of the primary goals of the project is to formulate new or improved policies for managing research and technology programs.

I will appreciate your giving high priority to requests for people and for other types of support. Substantial participation of some of your most able and experienced people is essential to the success of this project. Specific requests will be directed to you through my Deputy for Research and Technology. He, in turn, will be working closely with your representative on the steering committee, which has been monitoring and guiding the pilot programs, and which will continue in a similar role for the new project.

Further details can be ironed out at the Research and Engineering Policy Council meeting on July 12. However, if you disagree with this general approach, please notify me immediately. I see no other way of satisfying the Congress and the Secretary of Defense that we are getting our money's worth for RXD. Failure to satisfy these questions will almost certainly have serious consequences to those Program Categories.

/s/ HAROLD BROWN

Attachment:
Outline of Plans for
Project HINDSIGHT

Attachment

OUTLINE OF PLANS FOR PROJECT HINDSIGHT
A Study of Research and Technology Which Has Been Utilized
in Weapon Systems

July 1 - August 1

Colonel Raymond S. Isenson, ODDR&E, is appointed director of Project HINDSIGHT.

Each Military Department appoints one full time team captain to head the initial analysis group. In a series of meetings, Colonel Isenson, the team captains, and the steering committee make the final selection of the systems for initial study and agree on initial strategy and procedures.

Each team captain selects five members of his team who are to be assigned full-time to this project for a period of at least 2 months. Team members are to be selected for their technical competence as well as their special knowledge of the systems being studied. The appointments are made with the support of the Assistant Secretary (R&D) of the Military Department with which the team member is associated.

September 1

The entire group meets for a 3-day planning session in the Pentagon. The team captains, the director, and the steering committee will continue to meet at regular intervals throughout the study.

September 1 - November 1

The studies of the first group of weapon systems are performed and completed. The objective is to identify and describe the RXD events, determine the place and time of origin, and certain other factors including selected aspects of the management environment in the originating organization

November 1 - January 1

Replacement teams of five members each are formed around a second set of systems. The captains of the new teams will either be former team captains or be recruited from former team members. A second group of weapon systems are studied.

January 1 - March 1

Replacement teams are formed around a third group of systems.

March 1 - April 1

A draft of a summary report covering work to date will be prepared. At this time an assessment will be made regarding the continuation of the study.

If each of the teams can on the average analyze one system per month (i.e., 6 man months of work per system), then 18 systems will have been covered in the 6 month active study interval from September 1 to March 1. This will still be considerably less than half the inventory. It may be possible, once experience has been gained, to expand the study in the last few months by the formation of still more teams. This will be determined after the first three teams have completed their work.

The Military Departments will provide the captain and team members with adequate travel funds and other support, including office space and secretarial services, at a central location.

## APPENDIX E

### Definition of a Research or Exploratory Development Event

9 August 1965

General Definition of an RXD Event

An RXD (research or exploratory development) Event consists of the occurrence of a novel idea and a subsequent period of activity during which the idea is examined or tested. The RXD Event differs from otherwise similar human endeavors solely in that the testing or examination is primarily scientific or technological exploration.

Within this definition the period of activity - and, thus, the Event--is typically of a relatively short duration, from a few weeks to a few months. For example: At some time in the past, the idea occurred to an individual or work group that a hydrodynamically generated gas journal bearing for a gyroscope rotor could enable improved gyroscope characteristics over other rotor bearings currently available. The activity of interest, or Event, would consist only of so much as involved either a theoretical examination of the influence of bearing geometry on static and dynamic load-carrying capacity or a simple demonstration that a rotorlike mass could be supported on a hydrodynamically generated gas bearing journal. In other words, only the initial investigation adequate to demonstrate technical feasibility of the fundamental idea is included. It is important to note that this Event does not extend to a prototype gyro development.

Special Considerations

For purposes of the Department of Defense study of RXD effectiveness, those Events that contributed to developing a weapon or other military system or a military capability are of primary interest. A noncontributing Event might be of interest if the idea has been tested and is recognized as continuing to be of a high potential value but, for some technical reason, has not yet been exploited.

Finally, the matter of idea novelty warrants clarification. The RXD effectiveness study is addressed to the ascertaining of environmental factors associated with the successful prosecution and utilization of results of RXD. It can be safely assumed that a given idea would get the same treatment whether or not it was in fact novel—as long as the coworkers and supervisors of the innovator thought it to be novel. The criterion for novelty, then, is solely the contemporary opinion of the immediate sponsors of the idea.

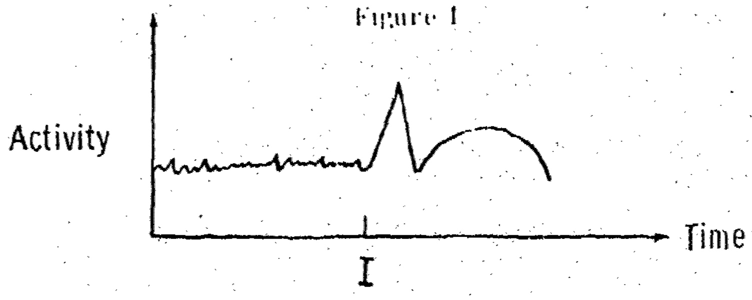
Interface Activity

Based on the above definition of an RXD Event, the history of the development of a new device or component can be expected to contain a

number [illegible] identifiable Events, some [illegible] sequentially.

Diagrammatically, an R&D Event may be shown [illegible] as in Figure 1.

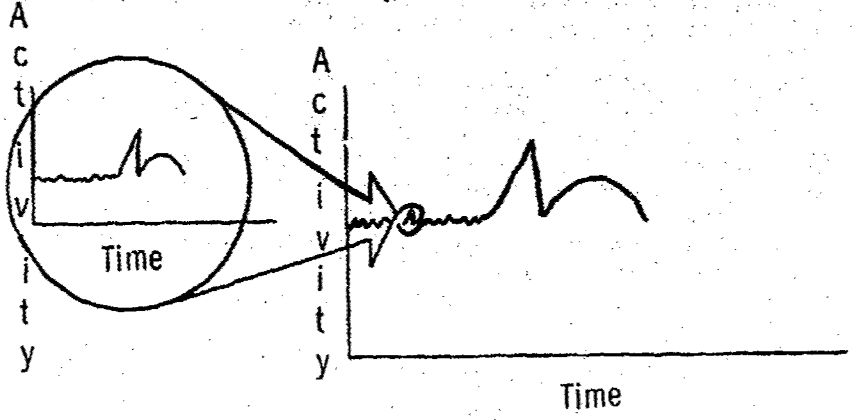
Figure 1




Prior to the occurrence of the idea (at I) or flash of inspiration, the innovator was involved in the acquisition of knowledge, through schooling or experience, that coincidentally was pertinent to the idea. Each of the minor excursions to the left of I indicates the acquisition of a bit of knowledge. These bits consist of technical know-how, operating environmental factors and, perhaps, operational requirements. At I, some triggering element enabled the culminating of all of the precedents into the idea. Subsequently, the idea is shown to be under active investigation.

Continuing with the generalization, assume that the output of the above Event is in some manner related to another innovator. If the latter individual makes use of the information in the developing of another idea, the information concerning the first Event becomes one of the minor excursions in the latter's knowledge-accrual diagram, as in Figure 2.

**Figure 2**



By interface activity is meant simply the manner in which the knowledge generated by the first innovator is transferred to the second. Examples of interface activity are: the publishing or presenting of a technical paper, an informal technical discussion among colleagues, attempts on the part of the first innovator to sell his idea to a potential customer, or the announcement of a patent award.

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## APPENDIX C

### RXD Event Description

1. Title

A short descriptive title identifying the activity (e.g., development, demonstration, investigation, study, etc.) which culminated in understanding of phenomena, demonstration of principles, or specific embodiment of principles (e.g., technique, device, material, etc.).

[Note: An RXD Event is conceived here as corresponding to a period of technical activity with a well-defined end point (e.g., the preparation of a report, presentation of a technical paper at a professional society meeting, patent disclosure, demonstration of feasibility of an idea by mathematical analysis or breadboard or brassboard model, etc.). Typically a creative or innovative act is involved. Care should be taken to avoid (a) inclusion of normal engineering activity within the contemporary state of the art, (b) lumping a number of RXD Events into an ill-defined class of such activity, and (c) confusing manufactured hardware with RXD Events.]

2. Weapon System

Name, including the standard nomenclature and the common name if needed for easy identification.

3. Subsystem

Reference to an analysis of the weapon system into immediate and separately identifiable constituents, arbitrarily adopted as standard for purposes of this study.

[Note: For this purpose, overall System Concept, Aerodynamic Configuration, etc., will be treated as subsystems where considered appropriate.]

4. Element

Reference to an analysis of the subsystem into immediate and separately identifiable components, considered as involving RXD Events.

[Note: For this purpose, the Subsystem Concept, or the subsystem itself, as defined above, will be treated as an element where considered appropriate.]

[illegible]

a. A [illegible] paragraph [illegible] Event, [illegible] contribution [illegible] possible, [illegible] paragraph should include [illegible] materials, techniques, publications, [illegible]

b. A [illegible] statement of the relationship of the RXD Event, [illegible] ascribed [illegible] to the contemporary [illegible] (e.g., the first example of the application [illegible] techniques to perform a function, etc.)

c. A brief statement describing the relationship of the RXD Event to the system or subsystem performance or to the succeeding related application in the chain connecting it to the system in question.

6. Type of RXD Event

A short statement clarifying the generic nature of the Event, e.g., scientific research, exploratory materials development, manufacturing process development, patented invention resulting from design engineering, etc. (The purpose of this statement is to assist in classification of RXD.)

7. Key Personnel

The names of the individuals having significant roles in the RXD Event, with a brief description of each one's role, background and experience. (Every reasonable attempt should be made to get copies of the personal biography (résumé) of the individuals identified as having made a direct contribution to the RXD Event. These résumés should be appended to the Event Description form.) The key personnel may be employed in the organization where the RXD was performed, in a government project office or laboratory, or elsewhere.

8. Date of Event

The year in which the specific RXD Event activity terminated (see 1 above). A more detailed specification of the date should be included when available. A starting date (approximate or estimated if necessary), consistent with the interface activity preceding the RXD Event described in 13 below, should be indicated. These initial and final dates should also be consistent with the financial descriptions of item 12.

9. Duration

The approximate length(s) of time covered by the specific technical activity having the termination in 8 above.

10. Organization

Specific information on:

a. The organization,

b. The organizational subdivisions, and

c. The specific organizational components or project groups within which the RXD Event was either performed or conceived, or where significant supervisory or other related decision-making occurred, or

d. A brief description of the organization, including the interrelationships among a, b and c and/or any special features of [illegible] that help to clarify the nature of the organization.

[Note: Organizations other than that where the RXD Event was performed (e.g., a government project office or laboratory) may have played an important part in the RXD Event and should also be identified where appropriate.]

11. Organization Type

The generic types of organization corresponding to 10 above. This should contain sufficient descriptive material to clarify fully the types of organization and organizational subdivision in question, e.g., industrial (profit)—corporate—research laboratory, industrial (profit)—operating division—design engineering organization, university-operated Department of Defense research laboratory, etc. The purpose of this paragraph (see also 6 above) is to assist in the classification of organization types.

12. Financial Support

Specific information on:

a. The source(s) of funds. This should include information concerning both the internal accounting treatment of the funds used and the ultimate sources of funds. Where the work is sponsored by the government or other sources external to the organization (10 above), specific contract or subcontract numbers should be identified where possible. Where the decision is made by the organization (10 above) to initiate the activity represented by the RXD Event, the way in which the costs are recovered or treated should be clarified (e.g., the expression "company funds" should refer only to the nonrecovered expenditure of a company's earned surplus; where subsequent recovery in the sale of products or in negotiated overhead on government contracts is involved, it should be so stated).

b. The time duration of each source of funds.

c. The total cost corresponding to each source of funds. If the source supported more than the RXD Event in question, give an estimate, if necessary, of the portion attributable to the Event. In general, estimates should be given where specific cost data are either unavailable or withheld.

d. Where additional funding was required in order to bring the results of the RXD Event to a fully useful point without other intervening events, the total cost should be shown here. Alternatively, if the RXD Event occurred during the course of a laboratory sustained program in a technology, a rough idea as to the total annual program size should be entered. (This generally does not apply to the case of an RXD Event's occurring as part of a weapon-system development project where the event was funded as part of the project; and no entry is required in this paragraph.)

[Note: Cost information should be given in terms of total (i.e., fully burdened) cost and such estimates should be formed, where possible, if the accounting practice of the performing organization differs in this respect.]

13. System Interface Activity

a. Information concerning the way in which the RXD Event was utilized, that is, the steps by which it was incorporated either in subsequent, related RXD Events or systems or in 2, 3 or 4 above. Wherever possible, specific events should be identified, e.g., the preparation of a proposal, etc.

b. Information concerning prior RXD Events, system activity or incidents which contributed to, influenced, or provided a motivation for, the RXD in question. In particular, where government sponsorship of the RXD work is involved, state whether the technical initiative resided in the performing organization, the government, or elsewhere.

14. RXD Event Circumstances

Miscellaneous information relating to the RXD Event but not elsewhere classified. Management environmental information may be recorded here. Wherever, because of the nature of the RXD Event, it is possible to demonstrate a relationship between the cost of the RXD Event and the cost savings to the government of either the final weapon systems or specific delivered hardware, this information should be identified and reported here.

15. Sources

Documents, persons interviewed, etc.

Author: Telephone number:
Date of preparation:
Attachment: Example of RXD Event Description

Attachment to Appendix I

R&D Event Description [illegible]

1. Title: Concept of Tracking an Orbiting Satellite by Measuring the Doppler Shift (X 45)

2. System: Navy Navigational Satellite System

3. Subsystem: Tracking Station

4. Element: Doppler Shift

5. Technical Significance:

a. Origin, Technical Activity and Outcome:

This event is the conception and demonstration of determining the orbit of a near-earth satellite on a single pass by an accurate measurement of the Doppler shift pattern in the radio signals transmitted by the satellite. The Doppler effect is an apparent change in frequency caused by the relative motion between transmitter and receiver.

b. Relationship to Contemporary Science and Technology:

At the time of this event there were several methods of tracking satellites. Optical tracking instruments using the visible-light portion of the electromagnetic spectrum, such as the Baker-Nunn ballistic camera which determines angular position by photographing the vehicle against a star background, are highly accurate. However, their capability is limited by darkness, clouds and haze. Also, the data require specialized handling, sometimes delaying the output beyond the period of usefulness.

Infrared radiation from the satellite permits it to be tracked through some haze conditions, but infrared is absorbed by the lower atmosphere, limiting its detection in ground stations.

Radio tracking techniques included radar scanning for the direction of the strongest signal and interferometer comparison of signal phases received by separate antennas. Minitrack, which operates from the latter principle, depends on a transmitted frequency to establish the line of position between the satellite and the tracking station.

While Minitrack uses a small part of the Doppler shift to measure miss distances and cannot determine the orbit in a single pass, this event derives all six orbit parameters from the total Doppler shift in one pass. Using scalar as opposed to vector measurements allowed vast simplifications while retaining accuracy. For example, only small antennas with a minimum exposure were required. Bumblebee Series Report No. 276 was issued April 1958 and distributed to anyone interested in satellite tracking.

c. Relationship to Succeeding Development or to Future Performance:

This event was essential for the inverse conception of determining the receiver position by Doppler data when the satellite orbit is accurately known. This idea initiated the development of the Navy Navigational Satellite System.

6. Type of R&D Event: Research

7. Key Personnel:

Dr. William Guier, Theoretical Physicist, Research Center. Conceived the event with Weiffenbach. His flair with computers was a great aid in reducing the Doppler shift to digital form to develop computational techniques for extracting orbital data.

Dr. George Weiffenbach, Theoretical Physicist, Research Center. Conceived the event and was primarily responsible for the accurate measurement of the Doppler shift.

Henry Riblet, Supervisor, BID Group. Experience in missile telemetry contributed to his setting up electronic equipment for the acquisition of experimental data.

Dr. R. R. Newton, Theoretical Physicist, Research Center. Assisted in theoretical analysis from the standpoint of celestial mechanics. Also assisted in programming.

8. Date of Event:

a. Termination: April 1958
b. Initiation: October 1957

9. Duration: Six months

10. Organization:

a. Johns Hopkins University
b. Applied Physics Laboratory
c. Research Center
d. The Research Center participated in many phases of basic unapplied investigation.

11. Organization Type: Government laboratory

12. Financial Support:

a. Source: In-house Task D (D-54) funds for basic research
b. Duration: Six months
c. Amount: Estimated $14,000

a. [illegible] Activity:

[illegible] launched 12 September [illegible] as it passed the APL and Newfoundland tracking stations, it was established that Doppler measurements of the missile trajectory were in agreement with the radar extrapolation. The Doppler technique has been used to track all subsequent APL satellites and led to the development of the Navy Navigational Satellite System.

b. Previous Activity:

Guier and Weiffenbach gathered all the immediately available receiving equipment and tape recorders to listen to the U.S.S.R.' Sputnik I after its launch on 4 October 1957. From this crude tracking station they noticed a pronounced Doppler shift in the transmission frequency and realized that, if they could accurately calculate the shift, these calculations would tell all of the orbit parameters and provide a good tracking technique. This would particularly aid identification of Sputnik's signal which was in an overcrowded region of the RF spectrum.

14. RXD Event Circumstances:

Dr. Frank McClure, Chairman of the Research Center, was skeptical of the possibility of accurately tracking a satellite with the Doppler technique; however, he supported a serious continuation of the initial investigation although no practical application was in sight at this time. Originally the orbital parameters were worked out with a slide rule, but APL fortuitously acquired a Univac 1103 which permitted much quicker, more accurate computations. Because the machine was new and priorities had not been established, the computer was available day and night. C. V. Bitterli, who worked with the computer, became very interested in the Doppler theory and creatively experimented with computer input and calculations. After two months of study, the Doppler curve looked more and more sensitive and unique, and its reliability in predicting orbit was much greater than anticipated. Eventually, good tape recorders and sophisticated radio tracking equipment were acquired to validate the Doppler method.

Important to the success of this event were the freedom allowed Guier and Weiffenbach and the acquisition of the Univac 1103 at a critical time. The enthusiasm generated by the key participants led many individuals to work on their own time. In early 1958 a geodesist from the Army Map Service, O'Keefe, somehow found out about the Doppler research at APL, gave new encouragement to the investigators, and also indicated some further questions to be answered. He was the first outside of APL to recognize the significance of the Research Center's work. Although the Naval Research Laboratory was concurrently doing related work with Minitrack and Vanguard, no interest was shown in APL's studies.

IV. Sources:

Persons interviewed:

Dr. George Weiffenbach
Glen San Lwin

Documents:

Guier, W. H., and Weiffenbach, G. C. [illegible] Applied Physics Laboratory, The Johns Hopkins University, Bumblebee Series, Report No. 276, April 1958.

[illegible], May 1958, a résumé.

Author: B. Patterson, Jonker Corp.

Telephone number: 202, 544-2665

Date of preparation: 11 May 1966

# APPENDIX D

## Summary of RXD Events

*Note*: Numbers omitted from the consecutive series represent reports withdrawn from the study.

# APPENDIX D

## SUMMARY OF RXD EVENTS

| Serial Number | Title | Year (Termination) | Organization Type |
|---|---|---|---|
| 0001 | Demonstration of a Spread Spectrum Tie-in Capability | 1952 | Government Laboratory |
| 0002 | Development of the Remote Binary Frequency Tuning Technique | 1960 | Profit Laboratory, Industrial |
| 0003 | Development of an Automatic Antenna Coupler for High Frequency Radio Equipment | 194[illegible] | Government Laboratory |
| 0004 | Invention of Control Panel Edge Lighting | 1947 | Government Laboratory |
| 0005 | Recognition of the Doppler Principle for Use in Aircraft Ground Velocity Measurements | 194[illegible] | Government Laboratory<br>Profit Laboratory, Industrial |
| 0006 | Study and Development of FM-CW Doppler Radar | 1953 | Profit Laboratory, Industrial |
| 0007 | Study and Investigation of Digital Computer Technology | 1957 | Government Laboratory |
| 0008 | Invention of Time-Shared Vertical Scale Propulsion Instrument | 1960 | Government Laboratory |
| 0009 | Development of a Lightweight Precision Gyro Compass | 1949 | Government Laboratory<br>Profit Laboratory, Industrial |
| 0010 | Conception of the Central Air Data Computer | 1950 | Government Laboratory |
| 0011 | Discovery of the Biocidal Properties of Fuel Anti-Icing Compound | 1959 | Profit Laboratory, Industrial |
| 0012 | Mathematical Demonstration of a Theoretical Turbofan Engine | 195[illegible] | Government Laboratory |
| 0013 | Conception of JT-3D Front Fan Turbofan | 1958 | Profit Laboratory, Industrial |
| 0014 | Invention of Zero-Length Inlet | 1961 | Profit Laboratory, Industrial |
| 0015 | Bifurcated Long-Duct Exhaust System | 1961 | Profit Laboratory, Industrial |

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SUMMARY OF END EVENTS ([illegible])

| Serial Number | Title | Year (Termination) | Organization [illegible] | [illegible] | [illegible] |
|---|---|---|---|---|---|
| [illegible] | Dutiged Nickel-Cadmium Coating for Corrosion Resistance of Low Alloy Steels | 1951 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0017 | Development of a New Coating Technique for Oxidation Protection of Nickel Base Superalloys in Gas Turbine Engines | 1959 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0018 | Fabrication of Compressor Weldment from Titanium Alloys | 1955 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0019 | Invention of Oil Cooling System for Turbo Fan Engines | 1962 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0020 | Development of a Vacuum Induction Melting Process | 1954 | Profit Laboratories, Industrial | [illegible] | [illegible] |
| 0021 | Development of the 6A1-4V Titanium Alloy | 1951 | Government Laboratory<br>Nonprofit Laboratory, [illegible]<br>Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0022 | Use of Titanium Alloys for Compressor Disks and Blades | 1951 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0023 | Use of Synthetic Rubber Viton A for Sealing Rings | 1957 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0024 | Short Discriminator Circuit for Fire Detector Control Box | 1963 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0025 | Development of a Wind Tunnel Technique for Visualization of Air Flow Vorticity | 1965 | Profit Laboratory, [illegible] | [illegible] | [illegible] |
| 0026 | The Conception of Low Drag Cargo Access Doors | 1960 | Profit Laboratory, [illegible] | [illegible] | [illegible] |
| 0027 | Investigation of Post Buckling Behavior of Heated Skin Panels | 1964 | Profit Laboratory, [illegible] | [illegible] | [illegible] |
| 0028 | Development of Statistical Mechanical Property Data for 7079 Aluminum Alloys | 1962 | Profit Laboratory, Industrial | [illegible] | [illegible] |

SUMMARY OF R&D [illegible]

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0029 | Development of a Redundant Structure Analysis Method | 1959 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0030 | Development of a Fail-Safe Structure Analysis Method | 1959 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0031 | Concept, Development and Demonstration of Use of Ceramics and Resins for Tooling | 1960 | Government Laboratory<br>Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0032 | Shot-Peening Prior to Chromium Plating of High Strength Steel | 1957 | Government Laboratory | [illegible] | [illegible] |
| 0033 | Development and Feasibility Demonstration of an Electronic Servo Model | 1960 | Profit Laboratory, Industrial<br>Government Laboratory | [illegible] | [illegible] |
| 0034 | Development of a Computer Theory for Fail Operative Redundancy | 1961 | Profit Laboratory, Industrial<br>Government Laboratory | [illegible] | [illegible] |
| [illegible] | Development of a Laboratory Test Model Computer with Fail Operative Logic | 1962 | Profit Laboratory, Industrial<br>Government Laboratory | [illegible] | [illegible] |
| [illegible] | Conception of a Pitch Axis Feel Subsystem | 1961 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0037 | Conception of a Lift-Compensating Spoiler Speed Brake System | 1962 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible] | Development of Raschel Net Crew Seat Components | 1958 | Government Laboratories | - | [illegible] |
| [illegible] | Conception of a Remote Aircraft Ice Detector | 1958 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible] | Development of the Theory of the Heat Transfer Function Through a Glass Pane | 1947 | University Laboratory<br>Government Laboratory | [illegible] | |
| [illegible] | Demonstration of a New Concept of Gear Reduction-Harmonic Drive | 1955 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible] | Demonstration of an Improved Cargo Release Sequencing Mechanism | 1962 | Profit Laboratory, Industrial | [illegible] | [illegible] |

SUMMARY OF PEIP EVENTS (Continued)

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0043 | Demonstration of an Automatic Lock Release Mechanism | 1963 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0044 | Parachute Opening Time Reduction Method | 1960 | Government Laboratory, University Operated Government Laboratory | [illegible] | [illegible] |
| 0045 | Development of Temperature Grease Thickeners | 1953 | Government Laboratory Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0046 | Development of a Direct Analog Pantograph | 1962 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0047 | Development of an Improved Flight Vehicle Wheel Test Method and Associated Instrumentation | 1962 | Profit Laboratories, Industrial Government Laboratory | [illegible] | [illegible] |
| 0048 | Experimental Validation of Directional Control | 1961 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0049 | Development of a Process for Producing High Reliability Soldered Connections in Missile and Space Systems | 1957 | Government Laboratory | [illegible] | [illegible] |
| 0050 | Application of a Technique Using Eddy Currents for Determining the Material Strength of Liquid Propellant Tanks | 1963 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0051 | The Development and Demonstration of a Technique To Statistically Determine the Reliability of Missile Hardware | 1964 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0052 | Development and Demonstration of a Technique for Molding the Butyl Seals for Propellant Tanks | 1965 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0053 | The Development and Demonstration of an Electron Beam Welding Technique Suitable for Use with Large Systems in a Production-Type Process | 1965 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0054 | Design and Demonstration of Non-Tip-Off Ground Missile Launcher | 1961 | Government Laboratory | [illegible] | [illegible] |

SUMMARY OF R&D [illegible]

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0055 | Validation of Analytical Approach to Optimized Launcher Design | 195- | Government Laboratory, Nonprofit Laboratory, University Operated | .22 | [illegible] |
| [illegible] | Development and Demonstration of the Helicopter-Transportable Missile Launcher | 1957 | Government Laboratory | [illegible] | [illegible] |
| 0057 | Invention of Non-Tip-Off Missile Launcher | 1950 | Government Laboratory | | [illegible] |
| [illegible] | Development and Use of Rationale of Rocket Exhaust Interaction with Launching Equipment | 195- | Government Laboratory | | |
| 0059 | Determination of Base Drag Characteristics of a Configuration with a Hot Gas Sustainer | 1963 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0060 | Development of a Theoretical Model for Determination of Base Drag Characteristics under the Influence of a Sustainer Jet | 1959 | Nonprofit Laboratory, University Operated | [illegible] | |
| [illegible] | Experimental Investigation of Generalized Base Drag Characteristics at Several Jet Pressure Ratios for Various Jet/Base Diameter Ratios | 1959 | Foreign [illegible] | [illegible] | |
| 0062 | Investigation of Generalized Base Drag Characteristics under the Influence of a Sustainer having Convergent/Divergent Nozzle | 1960 | Government Laboratory | [illegible] | |
| [illegible] | Experimental Investigation of Base Drag Characteristics of Central Sustainer Operating within an Annular Boost r | 1963 | Government Laboratory | [illegible] | [illegible] |
| [illegible] | Development of New Definition of Enemy Threat for Use in Derivation of Artil[illegible] System Performance Requirements by Deductive Analytical Pro[illegible] | 1965 | Government Laboratory | [illegible] | [illegible] |
| [illegible] | Development of Methodology for Comparing [illegible] Fire Support Systems | 1964 | Government Laboratory | [illegible] | [illegible] |

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| [illegible] | Title | [illegible] | [illegible] |
|---|---|---|---|
| [illegible] | Development and Environmental Static Test Facility to Handle Complete Missile Systems | [illegible] | [illegible] |
| [illegible] | Theoretical Analysis and Experimental Validation of Launcher Dynamics | [illegible] | [illegible] |
| [illegible] | Development and Demonstration of the Zero-Length Guidance Lightweight Research Launcher | [illegible] | [illegible] |
| [illegible] | Development and Demonstration of Thrust Vector Control for Use in Tactical Missiles | [illegible] | [illegible] |
| [illegible] | Prepackaged Liquid Propulsion Concept for Large Army Missiles | [illegible] | [illegible] |
| [illegible] | Development and Feasibility Demonstration of Piston Expulsion System for Storable Propellant Missiles | [illegible] | [illegible] |
| [illegible] | (Classified) | 1962 | Profit Laboratory, Industrial |
| [illegible] | (Classified) | 1958 | Government Laboratory |
| [illegible] | Annular Engine Concept and Feasibility Demonstrations | [illegible] | [illegible] |
| [illegible] | [illegible] Model Demonstration of an Oblique Shock as a Possible Means of Thrust Vector Control | [illegible] | [illegible] |
| [illegible] | [illegible] Demonstration of Liquid Secondary Injection for Thrust Vector Control | [illegible] | [illegible] |
| [illegible] | Demonstration of Feasibility of Secondary Injection Systems for Annular Engine | [illegible] | [illegible] |
| [illegible] | Development of a [illegible] Storage Piston [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] |

SUMMARY OF R&D EVENTS (Continued)

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0080 | Prediction and Compatibility Behavior of Fuel Rich Solid Propellant Gas Generator (SPGG) Gases with IRFNA Propellant | 1964 | Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| 0081 | Development and Validation of Oxidizer Neutralizer | 1965 | Government Laboratory, Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| 0082 | Development of UDMH (Unsymmetrical Dimethylhydrazine) for a Storable Liquid Fuel | 1953 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0083 | Development and Demonstration of Universal Squib for the LANCE Weapon System | 1965 | Profit Laboratory, Industrial | 5 | [illegible] |
| 0084 | Development of Antipropulsive Device | 1962 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0085 | Development of an Analog Computer Simulation Technique for Analysis of a Combustion Chamber Problem | 1965 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0086 | Research on Oscillatory Combustion | 1963 | Government Laboratory | [illegible] | [illegible] |
| 0087 | Exploratory Development of Variable Thrust Injectors for Storable Propellant Motors | 1963 | Government Laboratory | [illegible] | [illegible] |
| 0088 | Development of Analytical Technique for Successful Prediction of Liquid Secondary Injection Performance | 1964 | Profit Laboratory, Industrial | [illegible] | |
| 0089 | Use of 90° Segment of a Full-Scale Booster Engine to Accurately Measure Thrust Vector Control Performance | 1960 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0090 | Development of a Super Alpha Transistor Configuration | 1953 | Profit Laboratory, Industrial | | [illegible] |
| 0091 | Development of a Procedure and Equipment for Verifying the Linearity of Accelerometers | 1963 | Government Laboratory, Profit Laboratory, Industrial | [illegible] | [illegible] |

SUMMARY OF R&D EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0092 | Development and Demonstration of the Zero-Length Guidance Launcher | 1958 | Government Laboratories | [illegible] | [illegible] |
| 0093 | Conception and Development of a High Mobility Lightweight Launcher | 1965 | Government Laboratory, Profit Laboratories, Industrial | [illegible] | [illegible] |
| 0094 | Development of a High-Mobility Ground Support Equipment System | 1965 | Government Laboratories, Profit Laboratories, Industrial | [illegible] | [illegible] |
| 0095 | Development of Hot Gas Spin System | 1964 | Profit Laboratories, Industrial | [illegible] | [illegible] |
| 0096 | Development of Variable Solid-Propellant Gas Generator (SPGG) to Provide Spin Gases and Tank Pressurization for Boost and Sustain | 1964 | Profit Laboratories, Industrial | [illegible] | [illegible] |
| 0097 | Development of Improved Centrifuge for Verifying the Linearity of Accelerometers and Other Inertial Components under Varying Environmental Conditions | 1965 | Government Laboratory, Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0098 | Concept and Demonstration of Multisystem Test Equipment (MTE) | 1959 | Government Laboratories, Profit Laboratories, Industrial | [illegible] | [illegible] |
| 0099 | Conception of a Single Side Band High Accuracy Frequency Synthesizer | 1954 | Government Laboratories | [illegible] | [illegible] |
| 0100 | Concept of a Unique Digital Computer Logic | 1955 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0101 | Eight Channel Service Loads Recorder | 1957 | Profit Laboratory, Industrial, Government Laboratory | [illegible] | [illegible] |
| 0102 | Radome Lightning Protection Strips | 1948 | Non-profit Laboratory, Independent | [illegible] | [illegible] |
| 0103 | Invention of Rotating Rectifier and A. C. Exciter for Alternating Current Generator | 1949 | Profit Laboratory, Industrial | [illegible] | [illegible] |

SUMMARY OF RND EVENTS [illegible]

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0104 | Recognition and Investigation of the Catastrophic Nature of Hydrogen Contamination in Titanium Alloys | 1954 | Government Laboratory | | |
| 0105 | Lightning Protection of Fuel Systems | 1961 | Nonprofit Laboratory, Independent | | |
| 0106 | Thiokol Based Integral Fuel Tank Sealing Compound | 1946 | Government Laboratory, Profit Laboratories, Industrial | | |
| 0107 | Flutter Phenomena of All-Moveable Stabilizer | 1954 | Government Laboratory | | |
| 0108 | Flutter Safety for Aircraft with T-Tails | 1952 | Government Laboratory | | |
| 0109 | Flutter Safety for Swept Wing Aircraft | 1948 | Government Laboratory | | |
| 0110 | Full Scale Fatigue Test Requirements | 1949 | Government Laboratory | | |
| 0111 | Control of Sonic Fatigue | 1955 | Government Laboratory | | |
| 0112 | Establishing Sonic Fatigue Design Procedures | 1959 | Profit Laboratory, Industrial | | |
| 0113 | Exploratory Development of Aircraft Window Stretched Acrylic Plastic Material | 1953 | Government Laboratory, Profit Laboratory, Industrial | | |
| 0114 | Adhesive Bonded Metal Sandwich Construction for Aircraft | 1955 | Government Laboratory | | |
| 0115 | High Strength Welds in SAE 4340 Steel Used for Structural Components | 1952 | Government Laboratory, Nonprofit Laboratory, Independent | | |
| 0116 | Investigation of the Properties of Glass | 1956 | Government Laboratory | | |
| 0117 | Joggling of Extruded Wing Panels | 1962 | Profit Laboratories, Industrial | | |
| 0118 | Development of High Strength, High Resilience Silicone Elastomeric Materials | 1965 | Profit Laboratory, Industrial | | |

SUMMARY OF R&D EVENTS (Continued)

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0119 | Development of Small Bend Radii in Aluminum Sheet by Compressive Roll Forming | 1962 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0120 | Development of Nondestructive Tests for Adhesive Bonded Structures | 1956 | Government Laboratory, Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| 0121 | Invention of a Concept for a Wheel Deflation Device | 1953 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0122 | Landing Impact Loads | 1947 | Government Laboratory | [illegible] | [illegible] |
| 0123 | Fatigue Effects During Ground Operations | 1956 | Government Laboratory, Nonprofit Laboratory, Independent | [illegible] | [illegible] |
| 0124 | Aileron Effectiveness | 1945 | Government Laboratory | [illegible] | [illegible] |
| 0125 | Electronic Equipment Cooling System | 1951 | Government Laboratory | [illegible] | [illegible] |
| 0126 | Air Conditioning Load Requirements for Aircraft Compartments | 1952 | Government Laboratory | [illegible] | [illegible] |
| 0127 | Invention of a Jet Nozzle for Windshield Air Blast Rain Removal | 1953 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0128 | Development of Numerically Controlled Machine Tool | 1952 | Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| 0129 | Development of Automatically Programmed Tools (APT) for Numerically Controlled Machining Operation | 1959 | Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| [illegible] | Development of Vinylidene Fluoride-Hexafluoropropylene Elastomers for High Temperature Fluid Resistant Seals | 1956 | Government Laboratory | [illegible] | [illegible] |
| [illegible] | Development of Titanium Reference Alloys and Analytical Techniques for Compositional Analysis of Titanium Metal | [illegible] | Government Laboratory, Profit Laboratory, Industrial, [illegible] | [illegible] | [illegible] |

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| Serial Number | Title | Year | [illegible] | [illegible] | [illegible] |
|---|---|---|---|---|---|
| [illegible] | Development of an Adjustable ... Demonstration of a Force-Balance Accelerometer | [illegible] | [illegible] | | [illegible] |
| | [illegible] Attitude Direction [illegible] | [illegible] | [illegible] | [illegible] | |
| 0154 | Invention of Force-Wheel-Steering | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | Development of an Electronic Device for Missile Guidance and Control Electronics' Switching | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | Development of a High-Precision Centrifuge | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | Development and Demonstration of the Original Donner Model 4310 Accelerometer | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | Invention of the Servo Accelerometer | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | Derivation and Publication of the [illegible] | [illegible] | [illegible] | | [illegible] |
| [illegible] | Development of a Chopper-Stabilized [illegible] Current Amplifier with Low Drive and Wide Band-Width Characteristics | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible]-Type Cells for Improved [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | Demonstration of the Principle of Statistical [illegible] Period Processing | [illegible] | [illegible] | [illegible] | |
| [illegible] | Development of Phase Stable [illegible] Magnetic Recording Techniques | | [illegible] | [illegible] | [illegible] |
| [illegible] | Demonstration of the Concept of [illegible] | [illegible] | [illegible] | | |
| [illegible] | [illegible] | | [illegible] | | |
| [illegible] | [illegible] | | [illegible] | | |

| | | | |
|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | 1961 | [illegible] |
| [illegible] | Development of the Laminated High Power Traveling Wave Tube | 1961 | [illegible] |
| [illegible] | Development of the QKS 1120 Amplitron | 196[illegible] | [illegible] |
| 1[illegible] | Development of High Power Circulators | 1961 | [illegible] |
| 1[illegible] | Basic Design Development of the Ferrite Duplexer | 1961 | [illegible] |
| 17[illegible] | Demonstration of Hydrogen Thyratron | 1942 | [illegible] |
| [illegible] | Elimination of Gas Cleanup in Hydrogen Thyratron | 1944 | [illegible] |
| 154 | Development of Reentrant Anode Seal | 1944 | Government La[illegible] |
| 1[illegible] | Development of Hydrogen Thyratron Reservoir | 194[illegible] | Government La[illegible] University [illegible] |
| [illegible] | High Power Hydrogen Thyratron Development | 1951 | Government La[illegible] |
| [illegible] | [illegible] Low-Emission Film Coating [illegible] Waveguide Windows | [illegible] | [illegible] |
| [illegible] | Development of the Short Slot Hybrid [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | | |
| [illegible] | [illegible] of Techniques for [illegible] Writing [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] |

SUMMARY OF R&D [illegible]

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0168 | Development of a Magnetostrictive Video Storage Device | 1955 | Profit Laboratories, Industrial | [illegible] | [illegible] |
| 0169 | Demonstration of the Radar Azimuth Converter, Multibeam Radar | 1962 | Profit Laboratories, Industrial Government Laboratory | [illegible] | [illegible] |
| 0170 | Demonstration of a Data Converter for the Naval Tactical Data System (NTDS) | 1962 | Profit Laboratory, Industrial Government Laboratory | [illegible] | [illegible] |
| 0171 | Demonstration of Interface Data Conversion, Shipboard Radar | 1963 | Nonprofit Laboratory, Independent Profit Laboratory, Industrial Government Laboratory | [illegible] | [illegible] |
| 0172 | Demonstration of Digital Data Stabilization Computation, Multibeam Shipboard Radar | 1960 | Profit Laboratory, Industrial Nonprofit Laboratory, Independent | [illegible] | [illegible] |
| 0173 | Demonstration of Elevation Scanning and Power Management Control, Multibeam Frequency Scan 3-D Radar | 1960 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0174 | Development of an Integrated Circuits Warhead Fuze Programmer | 1964 | Government Laboratory | [illegible] | [illegible] |
| 0175 | Development of a Squib-Operated Boost Termination Valve for Packaged Liquid Propulsion | 1961 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0176 | Demonstration of the Feasibility of the Coaxial Nozzle for Step-Thrust Engine Operation to Meet Missile B Requirements | 1961 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0177 | Conception and Development of the Pivoting Front Support Launcher | 194- | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0178 | EOD Device Invention and Feasibility Study | 1965 | Government Laboratory | [illegible] | [illegible] |
| 0179 | Development and Demonstration of Methods for Applying Human Factors Engineering to a Total Weapons System | 196- | Government Laboratories Profit Laboratory, Industrial | [illegible] | [illegible] |

SUMMARY OF R&D EVENTS (Continued)

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0180 | Printed Circuit Switch Decks | 1962 | Government Laboratory | [illegible] | [illegible] |
| 0181 | Dual Voltage Thermal Battery | 1965 | Government Laboratory Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0182 | Development of Improved Electrical Connector | 1962 | Profit Laboratory, Industrial Government Laboratories | [illegible] | [illegible] |
| 0183 | Development of Sequential Testing Procedures | 1944 | Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| 0184 | Development of Theory and Statistical Techniques for Life Testing | 1954 | Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| 0185 | Development of Techniques for Determining Electric and Magnetic Polarizabilities of Apertures | 1950 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0186 | Hydrogen Thyratron Study | 1955 | Profit Laboratory, Industrial Government Laboratory | [illegible] | [illegible] |
| 0187 | Ceramic Hydrogen Thyratron Development | 1957 | Profit Laboratory, Industrial Government Laboratory | [illegible] | [illegible] |
| 0188 | Device for Determining the Occurrence of Stress Corrosion of Materials in Long Term Storage | Continuing | Government Laboratory | [illegible] | [illegible] |
| 0189 | Test Methods and Equipment for Evaluation of Inertial Components in a Spinning and Coning Environment | 1965 | Government Laboratory | [illegible] | [illegible] |
| 0190 | Specification on Deterioration and a Simplified Method for Maintaining It in an Updated Status | 1965 | Government Laboratory | [illegible] | [illegible] |
| 0191 | Hot Gas Relief Valve (HGRV) for Expulsion System Pressure Control | 1965 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0192 | Methods ... for Obtaining Data on Multicomponent Forces of Rocket Engines | 1967 | Government Laboratory Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0193 | Telemetry Calibration Techniques | 1964 | [illegible] | [illegible] | [illegible] |

| | | |
|---|---|---|
| | [illegible] Test [illegible] Batteries | [illegible] |
| | [illegible] meter System for [illegible] Measuring Acceleration [illegible] | [illegible] |
| | [illegible] Digital Simulator | [illegible] |
| | Development of Ground Support Equipment [illegible] and Prefire Tester for [illegible] Missile (Test Set AN [illegible]-24) | [illegible] |
| | [illegible] Investigation [illegible] Artillery Missile | [illegible] |
| | Development of an Economical Process for Producing a High-Permeability Magnetic Material with a Rectangular Hysteresis Loop | [illegible] |
| | Development of [illegible] Liquid [illegible] Hardware | [illegible] |
| | [illegible] | [illegible] |

| Serial Number | Title | | |
|---|---|---|---|
| [illegible] | Development of Theory of Se[illegible] Testing for Exponential Distr[illegible] | | [illegible] |
| [illegible] | Development of the Varactor | | [illegible] |
| [illegible] | Development of an Accelerometer [illegible] Accuracy and Low-Cost Require[illegible] | | [illegible] |
| 21[illegible] | Development of Mathematical M[illegible] Reliability | | [illegible] |
| 211 | Development of Microwave Prin[illegible] Design Techniques | | [illegible] |
| [illegible] | Establishment of Design Criteria [illegible] Pulse Transformers | | [illegible] |
| 213 | Development of Waveguide Rotar[illegible] | | [illegible] |
| 214 | Development of Measurement and [illegible] niques for High Power Microwave C[illegible] | | [illegible] |
| 215 | Development of Hydrogen Diode | | [illegible] |
| 21[illegible] | Classified | [illegible] | [illegible] |
| [illegible] | Classified | [illegible] | [illegible] |
| [illegible] | Classified | [illegible] | [illegible] |
| 21[illegible] | Classified | [illegible] | [illegible] |
| [illegible] | Classified | [illegible] | [illegible] |
| [illegible] | Classified | [illegible] | [illegible] |
| 222 | Classified | [illegible] | [illegible] |
| [illegible] | Classified | [illegible] | [illegible] |

SUMMARY OF [illegible]

| Serial Number | Title | Year (Termination) | Organization [illegible] | [illegible] | [illegible] |
|---|---|---|---|---|---|
| [illegible] | (Classified) | 1961 | [illegible] | | [illegible] |
| [illegible] | (Classified) | 1961 | [illegible] | [illegible] | |
| 022[illegible] | (Classified) | 1965 | Government Laboratory; Industry-Operated Government Laboratory | | [illegible] |
| 022[illegible] | (Classified) | 196[illegible] | Government Laboratory | [illegible] | [illegible] |
| [illegible]228 | (Classified) | 1965 | Government Laboratory; University-Operated Government Laboratory | [illegible] | [illegible] |
| 022[illegible] | (Classified) | 1963 | University-Operated Government Laboratory | [illegible] | [illegible] |
| 0230 | (Classified) | 195[illegible] | Government Laboratory | [illegible] | |
| 0231 | (Classified) | 1954 | Government Laboratory; Industrial Profit Laboratory | [illegible] | [illegible] |
| 0232 | (Classified) | 1955 | Government Laboratory | [illegible] | [illegible] |
| 0233 | (Classified) | 196[illegible] | Government Laboratory | [illegible] | |
| 0234 | (Classified) | 1959 | Government Laboratory | | |
| 0235 | (Classified) | [illegible] | Government Laboratory | [illegible] | |
| [illegible] | (Classified) | 1965 | Government Laboratory | [illegible] | |
| [illegible]237 | (Classified) | [illegible] | Government Laboratory; Industrial [illegible] | [illegible] | |
| 02[illegible] | Use of Carboxyl-Terminated Polybutadiene (CTPB) Based Propellant in Full-Scale Solid Rocket Motors | 1960 | Government Laboratory; Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible]240 | Invention of Liquid Injection Thrust Vectoring | 195[illegible] | [illegible] | | [illegible] |
| [illegible]247 | Discovery of a Curing Agent to Yield a Stable Carboxyl-Terminated Polybutadiene (CTPB) Propellant | 1962 | Profit Laboratory, Industrial | [illegible] | [illegible] |

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[illegible]

| Serial No. [illegible] | [illegible] | Year [illegible] | [illegible] |
|---|---|---|---|
| [illegible] | Development of [illegible] Nozzle | [illegible] | [illegible] |
| [illegible] | [illegible] Coating System for Missile Silos, [illegible] | [illegible] | [illegible] |
| 0244 | Microelectronics | [illegible] | [illegible] Profit Laboratories, Industrial |
| 0245 | [illegible] Spacer Assembly | Continuing | Profit Laboratory, [illegible] |
| 0246 | Development of High Strength Glass [illegible] Reinforcements [illegible] for Structural Plastics | [illegible] | Government Laboratory; Profit Laboratories, Industrial |
| [illegible] | Development of a High, Accurate [illegible] System | [illegible] | Profit Laboratory, Industrial |
| 0248 | Use of Integrated Circuits | [illegible] | Profit Laboratory, Industrial |
| 0249 | Development of Microminiature Multilayer Circuit Boards | [illegible] | Profit Laboratory, Industrial |
| 0250 | Development of Production Processes for Ceramic Printed Circuits | 1962 | Profit Laboratory, Industrial |
| 0251 | [illegible] Resistors for Stable Elements | [illegible] | Profit Laboratory, Industrial |
| [illegible] | Development of [illegible] Angle Transducer (also called [illegible] Resolver, [illegible]) | [illegible] | Profit Laboratory, Industrial |
| [illegible] | [illegible] Accelerometer [illegible] | [illegible] | Profit Laboratory, Industrial |
| [illegible] | [illegible] | 1964 | Profit Laboratory, Industrial |
| [illegible] | [illegible] | 1963 | Profit Laboratory, Industrial |
| [illegible] | [illegible] | 1963 | Profit Laboratory, Industrial |

| [illegible] | [illegible] | Year [illegible] | [illegible] |
|---|---|---|---|
| [illegible] | [illegible] Interference | [illegible] | Profit [illegible] |
| [illegible] | [illegible] LASER [illegible] Relation [illegible] | Continuing | Profit [illegible] Industrial |
| [illegible] | Electrochemical Machining of Beryllium | [illegible] | Profit [illegible] Industrial |
| [illegible] | Development of Finned Cylindrical Propellant [illegible] Configuration | 196[illegible] | Profit Laboratory Industrial |
| [illegible] | Internal Flapper Valve Development | 195[illegible] | Profit Laboratory Industrial |
| [illegible] | Metallic Diaphragm Valve Actuator Development | 196[illegible] | Profit Laboratory Industrial |
| [illegible] | Design and Development of the MIT II. 1[illegible] Pendulous [illegible] Accelerometer [illegible] | 19[illegible] | Non Profit Laboratory University Operated |
| [illegible] | Radar Detection Theory | 195[illegible] | Government Laboratory |
| [illegible] | Radar Detection Theory | 195[illegible] | Government Laboratory |
| [illegible] | Radar Detection Theory | 195[illegible] | Non Profit Laboratory Independent |
| [illegible] | Radar Detection Theory | 19[illegible] | [illegible] Government Laboratory |
| [illegible] | [illegible] | 19[illegible] | Non Profit Laboratory University Operated |
| [illegible] | [illegible] | [illegible] | Profit [illegible] Industrial |
| [illegible] | [illegible] | 19[illegible] | Government [illegible] |
| [illegible] | [illegible] | 19[illegible] | Government [illegible] |
| [illegible] | [illegible] | 19[illegible] | Profit [illegible] |

| | | Year | | | |
|---|---|---|---|---|---|
| [illegible] | [illegible] Receiver [illegible] | 1954 | [illegible] | | |
| [illegible] | [illegible] of Planar Array Antennae | 19[illegible] | [illegible] | | |
| | [illegible] | | | | |
| [illegible] | Radar Detection Theory | 195[illegible] | Government La[illegible] University Operated | | |
| [illegible] | Use of Integrated Circuits in Portable Maintenance [illegible] Equipment | 1962 | Profit Laborat[illegible] Industrial | | |
| [illegible] | [illegible]stigation of Materials for Solid Delay Line | 1[illegible]4 | Government La[illegible] University Operated | | |
| [illegible] | [illegible] Conception and the Construction of an Experimental Model of a Fused Quartz Supersonic Delay Line Using the Mode Conversion Technique | 1945 | Government Laborat[illegible] University Operated | | |
| [illegible] | Development of Indium Bond Technique for Attaching Quartz Crystals to Fused Quartz | 1946 | Government La[illegible] | | |
| [illegible] | Development of Multiple Symmetric Polygonal Fused Quartz Supersonic Delay Line | 195[illegible] | Government La[illegible] | | |
| [illegible] | Development of Photoelectric Coding Techniques | 195[illegible] | Government La[illegible] | | |
| [illegible] | Development of Techniques for Mechanized Production of Optical Encoder-Disk Masters | 1955 | Profit Laborat[illegible] Industrial, Government Laborat[illegible] | | |
| [illegible] | [illegible] Techniques [illegible] | 195[illegible] | Profit Laboratory, Industrial | | |
| [illegible] | [illegible] Techniques for [illegible] | 196[illegible] | Profit Laborat[illegible] Industrial | | |
| [illegible] | [illegible] Techniques [illegible] | 19[illegible] | Profit Laboratory, Industrial | | |

SUMMARY OF [illegible]

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| [illegible] | Development of a Welding Technique for Attachment of Integrated Circuits | [illegible] | Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible] | Use of Sintered Copper Tungsten as Electrodes for Electrical Surge Arrestors | [illegible] | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 203 | Demonstration of the Feasibility of Hardened Buried MF Radio for a Communications Link | [illegible] | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 204 | Demonstration of the Use of Tuned Filter Circuits as Electrical Surge Arrestors | [illegible] | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 205 | Development of the First High Power, Medium Frequency Solid State Transmitter | 1961 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible] | The Concept and Feasibility Demonstration of Multiplexed Instructions in a Digital Computer | 1959 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 207 | Development of Solid-State Computer Circuitry | 1957 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 208 | Conception and Feasibility Demonstration of a Logic Simulator Program | 1959 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible] | The Conception and Invention of Etched (Printed) Circuits | 1949 | Government Laboratory | | |
| [illegible] | Development of a Plated Interconnection for Circuit Boards | 1957 | Profit Laboratory, Industrial | | |

SUMMARY OF RXD EVENTS (Continued)

| Serial Number | Title | Date (Approximate) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| [illegible] | The Conception and First Demonstration of a Small, High-Efficiency [illegible] Impeller Type Blower | [illegible] | Profit Laboratory, Industrial | | [illegible] |
| 0[illegible]2 | The Conception and First Demonstration of an Air-to-Air Heat Exchanger | [illegible] | Profit Laboratory, Industrial | [illegible] | |
| [illegible] | Conception of an Automatic Code Conversion Technique | 195[illegible] | Profit Laboratory, Industrial | | [illegible] |
| [illegible]4 | The Invention and Demonstration of Electron Beam Welding | 195[illegible] | Profit Laboratory, Industrial | | [illegible] |
| [illegible] | (Classified) | 1942 | Government Laboratory | | [illegible] |
| [illegible] | (Classified) | 1942 | Government Laboratory | [illegible] | [illegible] |
| [illegible] | (Classified) | 1943 | Government Laboratories | [illegible] | [illegible] |
| [illegible] | (Classified) | 1944 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible] | (Classified) | 1945 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| [illegible] | (Classified) | 1951 | Government Laboratory | [illegible] | [illegible] |
| [illegible] | (Classified) | 1951 | Government Laboratory; Profit Laboratory, Industrial | | |
| [illegible] | (Classified) | 195[illegible] | Profit Laboratory, Industrial | [illegible] | |
| [illegible] | (Classified) | 195[illegible] | Government Laboratory | | [illegible] |
| [illegible] | (Classified) | [illegible] | Government Laboratory | | |
| [illegible] | (Classified) | [illegible] | Government Laboratory; Profit Laboratory, Industrial | | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | | |

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SUMMARY OF [illegible]

| Serial No. of | Title | Year (Completed) | [illegible] |
|---|---|---|---|
| [illegible] | [illegible] of Techniques for a [illegible] Three-[illegible] Direct-View Storage [illegible] | [illegible] | [illegible] |
| [illegible] | Development of Direct-View Memory Tube Techniques | [illegible] | Government Lab[illegible] |
| [illegible] | Demonstration of an Integrating Storage Tube Technique Using Charge-Store Concept | 1960 | Government Lab[illegible] |
| [illegible] | Demonstration of a Memory Tube Technique | 1962 | Government Lab[illegible] |
| [illegible] | Development of Storage Screen [illegible] Technique for Electrostatic Direct-View Storage Tube | [illegible] | [illegible] |
| [illegible] | Development of a [illegible] Direct-View Storage [illegible] | [illegible] | [illegible] |
| [illegible] | Development of Techniques for an Axial [illegible] with Three Coaxially Arranged Writing Guns for Direct-View Storage Tube | [illegible] | [illegible] |
| [illegible] | Development of a Drum Memory | 1960 | Profit Laboratory, Industrial |
| [illegible] | Conception of an Integrated Automatic Field Artillery FDC System | [illegible] | Government Laboratory |
| [illegible] | Preliminary Feasibility Study of a Digital Computer | 195[illegible] | Government Laboratory |
| [illegible] | Demonstration of Need for and Feasibility of Field Artillery Digital Computers | 195[illegible] | Government Laboratory |
| [illegible] | [illegible] Magnetic Read-Write-Recover [illegible] for High-Density Recording | [illegible] | [illegible] |
| [illegible] | [illegible] Mechanism [illegible] Surface | [illegible] | [illegible] |

[illegible]

| Serial Number | Title | Year Completed | Organization | [illegible] | [illegible] |
|---|---|---|---|---|---|
| [illegible] | [illegible] Electromechanical Flexible Recording [illegible] | [illegible] | Profit Laboratory, Industrial | | |
| [illegible] | The Development of Solid State Diode Logic | 195[illegible] | Government Laboratory | | |
| [illegible] | Development of Numerical Techniques for Use in Tactical Field Artillery Computers | 1955 | Profit Laboratory, Industrial | 4 | [illegible] |
| [illegible] | Meteorological Message Based on Raw, Unweighted Data for Computer Use | 195[illegible] | Government Laboratory | | [illegible] |
| [illegible]51 | Development of Basic Algorithms for Electronic Digital Computers | 1955 | Government Laboratory | [illegible] | [illegible] |
| [illegible]52 | The Invention of the First Electronic Digital Computer | 1947 | Nonprofit Laboratory / University Operated | 45[illegible] | [illegible] |
| [illegible]53 | (Classified) | | | | |
| [illegible]54 | (Classified) | | | | |
| [illegible] | (Classified) | | | | |
| [illegible] | (Classified) | | | | |
| [illegible] | (Classified) | 1954 | Government Laboratory | [illegible] | [illegible] |
| [illegible] | (Classified) | | | | |
| [illegible] | (Classified) | | | | |
| | (Classified) | | | | |
| [illegible] | (Classified) | 195[illegible] | Nonprofit Laboratory, University Operated, Government Laboratory | | [illegible] |
| [illegible] | [illegible] | 195[illegible] | Government Laboratory | [illegible] | [illegible] |

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[illegible]

| Report Number | Title | Date of Publication | [illegible] |
|---|---|---|---|
| [illegible] | Classified | [illegible] | [illegible] |
| [illegible] | (Classified) | [illegible] | [illegible] |
| [illegible] | (Classified) | | |
| [illegible] | Classified | 1957 | [illegible] |
| [illegible] | Design, Development, and Testing of a Prototype Solid Propellant-Reciprocating Engine Research Torpedo | 1958 | Government [illegible] |
| [illegible] | Demonstration of a Solid-Turbine Torpedo Power Plant | 1959 | Government [illegible] |
| [illegible] | (Classified) | 1957 | Government [illegible] |
| [illegible] | (Classified) | | |
| [illegible] | Classified | | |
| [illegible] | (Classified) | 1960 | [illegible] |
| [illegible] | (Classified) | 1958 | Government [illegible] |
| [illegible] | The [illegible] of a [illegible]-Ring [illegible] | 1959 | [illegible] |
| [illegible] | (Classified) | | |
| [illegible] | (Classified) | 1961 | [illegible] |
| [illegible] | Classified | [illegible] | Government [illegible] |
| [illegible] | Classified | 1961 | Government [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] |

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SUMMARY OF [illegible]

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| [illegible] | The Design and Development of a Variable-Angle Torpedo Launcher | 194[illegible] | Government Laboratory | [illegible] | [illegible] |
| [illegible] | (Classified) | | | | |
| [illegible] | (Classified) | | | | |
| 0353 | (Classified) | | | | |
| 0354 | (Classified) | | | | |
| 0355 | (Classified) | 1958 | Government Laboratory | [illegible] | [illegible] |
| 0356 | (Classified) | 1958 | Government Laboratory | [illegible] | [illegible] |
| 035[illegible] | (Classified) | 1959 | Government Laboratory | [illegible] | [illegible] |
| 03[illegible] | (Classified) | 1948 | Government Laboratory; Government Laboratory, University Operated; Profit Laboratory, Industrial | [illegible] | [illegible] |
| 03[illegible] | (Classified) | 1957 | Profit Laboratory, Industrial; Government Laboratory | [illegible] | [illegible] |
| [illegible]90 | Concept of a Practical Satellite Navigation System | 195[illegible] | Government Laboratory, University Operated | [illegible] | [illegible] |
| 0391 | Concept of Two Coherent Frequencies to Permit Ionospheric Correction | 1957 | Government Laboratory, University Operated | [illegible] | [illegible] |
| 0392 | Demonstration of a Passively Controlled Crystal Oscillator for Satellite Use | 1959 | Government Laboratory, University Operated | [illegible] | [illegible] |
| 039[illegible] | Development of Vacuum Insulation for the Satellite Oscillator | 1960 | Government Laboratory, University Operated | [illegible] | [illegible] |
| 0394 | Development of a Lightweight Ultrastable Crystal Oscillator | 1961 | Government Laboratory, University Operated | [illegible] | [illegible] |

| Serial Number | Title | Year Terminated | Operated by |
| --- | --- | --- | --- |
| [illegible] | Development of a Thermostatically Controlled Satellite Oscillator | 196[illegible] | Government Laboratory, University Operated |
| [illegible] | Adaption of the Five Megacycle Fifth Overtone Crystal for Satellite Oscillator | 1962 | Government Laboratory, University Operated |
| [illegible] | Development of a Dual Oscillator and Oven | 1964 | Government Laboratory, University Operated |
| [illegible] | Development of a DC-to-DC Converter | 196[illegible] | Government Laboratory, University Operated |
| [illegible] | The Concept for Using a Phase-Locked Tracking Filter | 1959 | Government Laboratory, University Operated |
| 9400 | Development of a Spiral Satellite Antenna | 1959 | Government Laboratory, University Operated |
| 9401 | Modification of Solar Power System To Take Advantage of Stabilization Modes | 1961 | Government Laboratory, University Operated |
| 9402 | Development of a Magnetic Core Memory for Satellite Use | 196[illegible] | Government Laboratory, University Operated |
| 9403 | The Development of the No-Scan Detector | 1962 | Government Laboratory, University Operated |
| 9404 | Conception and Development of a Time Normalizer | 196[illegible] | Government Laboratory, University Operated |
| 9405 | The Development of Magnetic Drive Circuits for the Satellite Core Memory | 1961 | Government Laboratory, University Operated |
| 9406 | Discovery of Resonance Effects in Long Term Satellite Drift | 1964 | Government Laboratory, University Operated |
| 9407 | [illegible] Integration for Satellite Equations of [illegible] | [illegible] | [illegible] |

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| [illegible] | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| [illegible] | [illegible] for [illegible] | 1962 | Government Laboratory University Operated | | |
| | [illegible] of Damping [illegible] Gravity [illegible] Satellite | [illegible] | Government Laboratory University Operated | | |
| | [illegible] for Damping Satellite Oscillation | [illegible] | Government Laboratory University Operated | | |
| [illegible] | Magnetic Stabilization of an Orbiting Satellite | [illegible] | Government Laboratory University Operated | | |
| [illegible] | Development of a Radioisotope Power Supply for Satellites | [illegible] | Government Laboratory University Operated | | |
| [illegible] | [illegible] Development of a Satellite [illegible] | [illegible] | Government Laboratory University Operated | | |
| [illegible] | [illegible] Transistor [illegible] | [illegible] | Government Laboratory University Operated | | |
| [illegible] | [illegible] and Feasibility Demonstration [illegible] Channel | [illegible] | Profit Laboratory [illegible] | | |
| [illegible] | [illegible] | [illegible] | [illegible] | | |
| [illegible] | [illegible] | [illegible] | [illegible] | | |
| | [illegible] | [illegible] | [illegible] | | |
| | [illegible] | [illegible] | [illegible] | | |
| | [illegible] | | [illegible] | | |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 0421 | The Demonstration of Suitability of AISI 52100 Steel for Manufacture of Large-Caliber Forged Shell with Improved Fragmentation | 1964 | Nonprofit Laboratory, University Operated Government Laboratory | 107 | XD |
| 0422 | The Development of a Design Concept for a 152 mm Round | 1958 | Government Laboratory | 3 | XD |
| 0423 | Development of an Analytic Method for Estimating Center of Pressure and Normal Force Coefficients (Simmons-Wood Method) | 1954 | Government Laboratories | 50 | R |
| 0424 | The Development of Scaling Laws for Fluted Liners | 1958 | Government Laboratory | 1,000 | R |
| 0425 | Development of Spinning Wire Technique for Investigation of Large Spinning Shaped Charges | 1952 | Government Laboratory | 100 | XD |
| 0426 | The Development of a Multiple Flash Radiography System for Shaped Charge Research | 1953 | Government Laboratory | 50 | R |
| 0427 | Invention of a Compatible Two Bit at a Time Multiply and Divide Logic | 1958 | Profit Laboratory, Industrial | 3 | R |
| 0428 | Concept of Read Only Memory (Cold Storage) in a Digital Computer | 1957 | Profit Laboratory, Industrial | 30 | XD |
| 0429 | Development and Feasibility Demonstration of a Fully Shielded Type Magnetic Head for High-Density Recording in Magnetic Memories | 1954 | Profit Laboratory, Industrial | 15 | XD |
| 0430 | Feasibility and Demonstration of a Hydrodynamically Supported Multiple Recording Head Holder | 1960 | Profit Laboratory, Industrial | [illegible] | XD |
| 0431 | Multifrequency Clutter Study | 1964 | Profit Laboratory, Industrial | [illegible] | R |
| 0432 | Development of a Waveform with No Ambiguous Ranges or Velocities for Use with a Clutter Rejection Radar | 1965 | Profit Laboratory, Industrial | [illegible] | XD |

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SUMMARY OF RXD EVENTS (Continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 0433 | Development of a Rotating Phased Array Incorporating Aircraft and Scanning Motion Compensation | 1964 | Profit Laboratory, Industrial | 25 | XD |
| 0434 | Feasibility Model of Magnetic Disc Memory Unit Using an Autolubricated Air Bearing for Head to Disc Separation | 1954 | Profit Laboratory, Industrial | 150 | AD |
| 0435 | Concept and Feasibility Demonstration of Autolubricated Air Bearings for Use in a Magnetic Disc Memory | 1951 | Profit Laboratory, Industrial | 20 | XD |
| 0436 | The Concept and Feasibility of Rotating Magnetic Memories for Digital Computers | 1946 | Profit Laboratory, Industrial | [illegible] | XD |
| 0437 | Multilevel Logic System | 1958 | Profit Laboratory, Industrial | 12 | XD |
| 0438 | Development of Ceramic Transducer Elements | 1956 | Profit Laboratory, Industrial | | XD |
| 0439 | Study of Flow Noise | 1956 | Government Laboratory | | XD |
| 0440 | Concept of a Semiautomatic Test System for Digital Computers | 1958 | Profit Laboratory, Industrial | 25 | XD |
| 0441 | Concept of Paper Tape Canister for Memory Loading Program Tape | 1959 | Profit Laboratory, Industrial | 20 | XD |
| 0442 | Conception of Computer Error Detection Systems | 1958 | Profit Laboratory, Industrial | 50 | XD |
| 0443 | Concept of Organizational Maintenance for Digital Computers in the Field | 1958 | Government Laboratory | [illegible] | XD |
| 0444 | Development of Computer Test Concept and Associated Hardware | 1954 | Profit Laboratory, Industrial | [illegible] | AD |
| 0445 | Development of a Design for Main Battle Tank Armament System Firing Spin-Stabilized HEAT Shell Using Existing Fluted Liners | 1958 | Government Laboratory | 20 | R |
| 0446 | Establishment of Index Angle Concept for Adjusting Spin Compensation Frequency of Fluted Shaped Charge Liners | 1952 | Nonprofit Laboratory, University Operated | 40 | R |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 0447 | Development of Reusable Instrumentation to Monitor Shocks of Parachute Inflation, Water Entry and Bottom Impact of Launched Underwater Weapons | 1962 | Government Laboratory | 50 | XD |
| 0448 | Development of Special Neoprene Compound with High Tear Strength for Sleeves of Swaged Fittings | 1962 | Government Laboratory | 10 | XD |
| 0449 | Conception and Demonstration of a Modular Construction System for Mine Components | 1948 | Government Laboratory | 10 | XD |
| 0450 | Feasibility Established for System to Dislodge Mine Case from Mud by Generating Volume of Gas | 1955 | Government Laboratory | 100 | XD |
| 0451 | Study of Plastics for Optimum Compatibility with Electrolytes used in Electrochemical Timing Devices | 1953 | Government Laboratory | 50 | XD |
| 0452 | Development of Superior Antifouling Paint for Prevention of Marine Growths on Mine Cases | 1956 | Profit Laboratory, Industrial Government Laboratory | 75 | XD |
| 0453 | Development of a Technique for Nondestructive Determination of Structural Strength by Use of Differential Hydrostatic Pressure Test | 1951 | Government Laboratory | 15 | XD |
| 0454 | Conception and Demonstration of Controlled Collapse Hydrostatic Pressure Test | 1951 | Government Laboratory | 2 | XD |
| 0455 | Development of Technique for Simulation of Mine Response to Ships' Magnetic Fields | 1966 | Government Laboratory | 60 | XD |

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SUMMARY OF RXD EVENTS [illegible]

| Serial Number | Title | Year (Termination) | Organization Type | Funds [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0473 | (Classified) | 1956 | Government Laboratory | [illegible] | [illegible] |
| 0474 | (Classified) | 1948 | Government Laboratory | [illegible] | [illegible] |
| 0475 | (Classified | 1943 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0476 | (Classified) | 1944 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0477 | (Classified) | 1944 | Government Laboratory | [illegible] | [illegible] |
| 0478 | | | | | |
| 0479 | (Classified) | 1954 | Government Laboratory | [illegible] | [illegible] |
| 0480 | (Classified) | 1955 | Government Laboratory | [illegible] | [illegible] |
| 0481 | (Classified) | 1957 | Government Laboratory | [illegible] | [illegible] |
| 0482 | (Classified) | 1962 | Government Laboratory | [illegible] | [illegible] |
| 0483 | (Classified) | 1957 | Government Laboratory | [illegible] | [illegible] |
| 0484 | (Classified) | 1958 | Government Laboratory | [illegible] | [illegible] |
| 0485 | (Classified) | 1958 | Government Laboratory | [illegible] | [illegible] |
| 0486 | (Classified) | 1957 | Government Laboratory | [illegible] | [illegible] |
| 0487 | (Classified) | 1964 | Government Laboratories | [illegible] | [illegible] |
| 0488 | (Classified) | 1960 | Government Laboratories<br>Nonprofit Laboratory, University-operated | [illegible] | [illegible] |
| 0496 | (Classified) | 1952 | Government Laboratories | [illegible] | [illegible] |
| 0497 | (Classified) | 1955 | Government Laboratories | [illegible] | [illegible] |
| 0498 | (Classified) | 1951 | Government Laboratory | [illegible] | [illegible] |
| 0522 | (Classified) | 1957 | Government Laboratory | [illegible] | [illegible] |

SUMMARY OF R&D EVENTS (Continued)

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 0523 | (Classified) | 1959 | Government Laboratory | [illegible] | [illegible] |
| 0524 | (Classified) | 1956 | Government Laboratory | [illegible] | [illegible] |
| 0525 | (Classified) | 1956 | Government Laboratory, Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0526 | (Classified) | 1957 | Government Laboratory | [illegible] | [illegible] |
| 0527 | (Classified) | 1951 | Government Laboratory | [illegible] | [illegible] |
| 0528 | (Classified | | | | |
| 0529 | (Clas ified) | 1952 | Government Laboratory | [illegible] | [illegible] |
| 0530 | (Classified) | 1952 | Government Laboratory, Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0531 | (Classified) | 1944 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0532 | (Classified) | 1953 | Government Laboratory | [illegible] | [illegible] |
| 0533 | (Classified) | 1961 | Government Laboratory, Profit Laboratory, Industrial | [illegible] | [illegible] |
| 0534 | (Classified) | 1962 | Government Laboratory | [illegible] | [illegible] |
| 0562 | (Classified) | 1962 | Government Laboratory | [illegible] | [illegible] |
| 0563 | (Classified) | 1962 | Government Laboratory | | |
| 0564 | (Classified) | 1950 | Government Laboratory | [illegible] | |
| 0565 | (Classified) | 1951 | Government Laboratory | [illegible] | |
| 0566 | (Classified) | 1952 | Government Laboratory, Foreign Government, Nonprofit Laboratory, University-operated | [illegible] | [illegible] |
| 0567 | (Classified) | 1950 | Government Laboratory | [illegible] | [illegible] |
| 0568 | (Classified) | 1961 | Government Laboratory | [illegible] | [illegible] |
| 0569 | (Classified)1 | 1951 | Government Laboratory | [illegible] | [illegible] |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 3001 | Transonic and Supersonic Research on Delta-Winged/Canard-Controlled Missile Configurations | 1952 | Government Laboratory | -- | XD |
| 3002 | Development and Demonstration of the Use of Electronic Simulators To Evaluate the Ability of a Pilot to Guide an Air-to-Surface Missile | 1954 | Government Laboratory | 225 | XD |
| 3003 | Derivation of a Statistical Theory of Communication | 1942 | Government Laboratory, University Operated | 10 | R |
| 3004 | Experimental Validation of Wiener's Statistical Theory of Communication | 1950 | Government Laboratory, University Operated | 100 | R |
| 3005 | Development of an Antijam Technique for a Radio Link | 1952 | Profit Laboratory, Industrial | 5 | XD |
| 3007 | Experimental Investigation of the Compressive Yield Strength of Metals | 1960 | Profit Laboratory, Industrial | 25 | XD |
| 3008 | Development of a Quick-Start, Spring-Actuated Gyro Rotor and Uncage Mechanism | 1954 | Profit Laboratory, Industrial | 23 | AD |
| 3009 | Demonstration of the Feasibility of Using a Pyrotechnic-Generated Hot Gas To Drive a Gyro Rotor | 1960 | Profit Laboratory, Industrial | 7 | XD |
| 3010 | Development of a Gas-Operated Uncaging Mechanism for a Gyro Rotor | 1960 | Profit Laboratory, Industrial | 30 | XD |
| 3011 | Development of a Technique for Swaging a Hermetic Seal | 1960 | Profit Laboratory, Industrial | -- | XD |
| 3012 | Development of a Valveless Pressure-Relief Technique | 1960 | Profit Laboratory, Industrial | -- | XD |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 3013 | Development of a Parasitic Flare | 1957 | Government Laboratory | -- | XD |
| 3014 | Theory, Development and Test of Fused Salt Battery | 1945 | Foreign Government Laboratory | 49 | R |
| 3015 | Conception of Pyro-Fusing of Electrolytic Salts | 1946 | Government Laboratory | 1 | XD |
| 3016 | Demonstration of Feasibility of Thermal Battery | 1947 | Profit Laboratory, Industrial | 16 | XD |
| 3017 | Demonstration of Feasibility of High-Voltage Thermal Battery | 1950 | Profit Laboratory, Industrial | 426 | XD |
| 3018 | Conception of Heat Paper | 1951 | Profit Laboratory, Industrial | 10 | XD |
| 3019 | Development of Heat-Paper Production Techniques | 1954 | Government Laboratory, University Operated | 60 | XD |
| 3020 | Conception and Development of Leaf-Type Cell | 1952 | Profit Laboratory, Industrial Government Laboratory | 100 | XD |
| 3021 | Development of Thick-Metal Deposition Technique | 1953 | Profit Laboratory, Industrial Government Laboratory | 60 | XD |
| 3022 | Development of the Concept of a Packaged Liquid-Rocket Motor | 1953 | Profit Laboratory, Industrial | 130 | XD |
| 3024 | Invention of the Shear-Slide Device to Close-Couple the Release of Fuel and Oxidizer into a Rocket Combustion Chamber | 1953 | Profit Laboratory, Industrial | -- | XD |
| 3025 | Invention of Slotted-Keyhole Configuration Pressurizing Grain | 1956 | Profit Laboratory, Industrial | -- | XD |
| 3028a | Propellant Injector-Mixer Conception | 1942 | Government Laboratory | 50 | XD |
| 3029 | Study of Nonreactive Jet Mixing | 1957 | Profit Laboratory, Industrial | 404 | R |
| 3037 | Development of a Technique for Plasma-Jet Deposition of Rockide | 1964 | Profit Laboratory, Industrial | 163 | XD |

## SUMMARY OF RXD EVENTS ([illegible])

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 4001 | Development of Composite Solid Propellants | 1942 | Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| 4002 | Application of Thermosetting Polymers to Composite Solid Propellants | 1947 | Government Laboratory, University Operated | [illegible] | [illegible] |
| 4003 | Conception of Case-Bonded, Radial-Burning Solid Propellant Rocket Motor | 194[illegible] | Government Laboratory, University Operated | [illegible] | [illegible] |
| 4004 | Development of Castable, Double-Base Propellants | 1945 | Government Laboratories, University Operated | [illegible] | [illegible] |
| 4005 | Development of Fluid Injection for Thrust Vector Control | 1951 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4007 | Development of Polybutadiene Fuel-Binder | 1954 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 400[illegible] | Development of Polyurethane Fuel-Binder | 1955 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4009 | Use of Aluminum To Increase the Specific-Impulse of Solid Propellants | 1956 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4010 | Aluminum Additive for Control of Combustion Instability in Solid Propellant Rockets | 1956 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4011 | Development of Composite-Modified Double-Base Propellants | 195[illegible] | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4012 | Conception and Demonstration of the Pyrogen Igniter | 1956 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4013 | Exploratory Development of Thrust Reversal Methods for Solid Propellant Rocket Motors | 1956 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4014 | Conception and Demonstration of Thrust Vector Control (TVC) by Mechanical Spoilers (Jetavators) | 1956 | Government Laboratory | [illegible] | [illegible] |
| 4015 | Development of Swiveled Nozzle for Thrust Vector Control (TVC) | 1957 | Profit Laboratory, Industrial | [illegible] | [illegible] |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 4016 | Conception of Canted Rotatable Nozzle for Thrust Vector Control (TVC) | 1959 | Nonprofit Laboratory, University Operated | [illegible] | [illegible] |
| 4017 | Development of Nitroplasticized Polyurethane Composite Propellant | 1961 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4019 | Development of Consumable Electrode Vacuum Arc Melting Process for Forgeable Refractory Metals | 1944 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4020 | Development of Pyrolytic Graphite | | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4021 | Invention of Composite Silver Infiltrated Porous Tungsten Rocket Nozzle | 1960 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4022 | Conception and Development of Filament-Wound Cases for Solid Propellant Rockets | 1949 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4023 | Development and Analysis of Filament-Wound Closed-End Pressure Vessel | 1955 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4024 | Development of Reliable Integrated Circuits | 1964 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4025 | Development of High Temperature Shock Tube | 1950 | University Laboratory | [illegible] | [illegible] |
| 4026 | Identification of Transition Between Laminar and Turbulent Flow on Blunt-Nose Body in High-Speed Air Streams | 1956 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4027 | Recognition of the Inadequacy of Heat Sink for Re-Entry | 1955 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4028 | Prediction of Ablative Behavior and Flight Test of Quartz Heat Shield | 1959 | Profit Laboratory, Industrial | [illegible] | [illegible] |
| 4030 | Discovery of the Principle of Ablative Cooling | 1953 | Government Laboratory | [illegible] | [illegible] |
| 4032 | Development of a Useful Data Processor Using Digital Integrated Circuits | 1961 | Profit Laboratory, Industrial | [illegible] | [illegible] |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 4035 | Invention and Development of Shaped Line Explosive Charge | 1958 | Nonprofit Laboratory, Independent | [illegible] | XD |
| 4036 | Conception of Bare Missile, Air-Ejected Submerged Launching | 1956 | Profit Laboratory, Industrial | [illegible] | XD |
| 4039 | Development of Two-Degree-of-Freedom (Free) Gyroscope with a Spherical Hydrodynamic Gas Bearing Supporting the Gyro Wheel | 1956 | Profit Laboratory, Industrial | 225 | XD |
| 4040 | Conception and Demonstration of Integrated Semiconductor Circuits | 1958 | Profit Laboratory, Industrial | [illegible] | XD |
| 4041 | Development and Flight Test of the FEBE System | 1949 | Government Laboratory, University Operated | [illegible] | XD |
| 4042 | Development of an Improved Ballistic-Missile Guidance System | 1945 | Foreign Government Laboratory | -- | XD |
| 4043 | Development of Doppler Enabler | 1954 | Government Laboratory | 25 | XD |
| 4044 | Achievement of Twilight Astrotracker Capability | 1960 | Profit Laboratory, Industrial | 50 | AD |
| 4045 | Development of Raster-Chopper and Shutter-Scanning System | 1952 | Profit Laboratory, Industrial | 50 | AD |
| 4047 | Development of Disc Memory for Digital Navigational Computer | 1954 | Profit Laboratory, Industrial | [illegible] | XD |
| 4048 | Development of Pendulous Integrating Accelerometer | 1957 | Profit Laboratory, Industrial | [illegible] | XD |
| 4049 | Development of Gunsight Incorporating a Gyro as Rate Sensor and Analog Computer | 1941 | Nonprofit Laboratory, University Operated | [illegible] | XD |
| 4050 | Development of the Microsyn as a Precise Torque Generator for Application to Computing Gyroscopes | 1942 | Government Laboratory, University Operated | [illegible] | [illegible] |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | [illegible] | [illegible] |
|---|---|---|---|---|---|
| 4051 | Development of Digital Readout and Control of Gyros, Accelerometers and Platform Gimbals | 1957 | Profit Laboratory, Industrial | -- | AD |
| 4052 | Development of the Single-Degree-of-Freedom Integrating Rate Gyroscope | 1948 | Government Laboratory, University Operated | [illegible] | XD |
| 4053 | Adaptation of Pressure Sensing Device for Use as Engine Power Control | 1958 | Profit Laboratory, Industrial | 2 | AD |
| 4054 | Development of Digital Differential Analyzer for Aircraft Navigation | 1954 | Profit Laboratory, Industrial | -- | XD |
| 4058 | Development of the Variable-Position Inlet Diffuser | 1958 | Profit Laboratory, Industrial | 6 | AD |
| 4059 | Development of Fuel Antifreeze | 1959 | Profit Laboratory, Industrial | 15 | XD |
| 4060 | Development of a Reliable Low-Altitude Radar Altimeter | 1957 | Profit Laboratory, Industrial | 10 | XD |
| 4061 | Development of the Magnetic Suspension To Replace Jewel Bearings on the Gimbal Axis of Precise Gyros | 1959 | Government Laboratory, University Operated | 300 | XD |
| 4062 | Development of Guidance Concept Based upon Computation and Control of Velocity To Be Gained | 1955 | Nonprofit Laboratory, University Operated | 100 | XD |
| 4063 | Development of Hydrodynamically Generated Gas Journal and Thrust Bearings for Gyros | 1956 | Profit Laboratory, Industrial | 200 | XD |
| 4065 | Development of Missile Thrust Control Method | 1959 | Government Laboratory, University Operated | 1,300 | XD |
| 4066 | Development of Zero Length Nonvertical Missile Launch | 1959 | Government Laboratory, University Operated | 250 | XD |
| 4071 | Development of Epitaxial Deposition of Semiconductor Material | 1960 | Profit Laboratory, Industrial | 100 | R |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 4075 | Development of Propellant Additives to Inhibit Gun Tube Erosion | 1958 | Foreign Government Laboratory | -- | XD |
| 4078 | Development of Autofrettage Swaging | 1959 | Government Laboratory | [illegible] | XD |
| 4081 | Development of Revel Panel, Transit Time Alignment Compensation | 1958 | Government Laboratory | [illegible] | XD |
| 4082 | Development of Revel Panel, Reverberation Filtration | 1958 | Government Laboratory | 50 | XD |
| 4083 | Development of Revel Panel, Recognition of Noise-Limited and Reverberation-Limited Conditions | 1958 | Government Laboratory | [illegible] | XD |
| 4084 | Development of Revel Panel, Bilateral Automatic Gain Control | 1959 | Government Laboratory | 50 | XD |
| 4086 | The Design and Demonstration of a Low-Cavitation Propeller | 1955 | Government Laboratory, University Operated | [illegible] | XD |
| 4087 | Development of Rational Design Criteria for Counter-Rotational Propellers | 1959 | Government Laboratory | -- | XD |
| 4088 | Development of Hot-Gas Engine | 1956 | Profit Laboratory, Industrial | [illegible] | XD |
| 4092 | Development of an Effective and Reliable Influence Fuze for Acoustic Torpedoes | 1955 | Government Laboratory, University Operated | [illegible] | XD |
| 4093 | Formulation of H-6 Explosive | 1951 | Government Laboratory | [illegible] | XD |
| 4094 | Optimization of RDX/TNT/Al Mixture for Maximum Underwater Shock Energy | 1952 | Government Laboratory | [illegible] | XD |
| 4095 | Determination of Most Desirable Compromise Among Shock and Bubble Energies for an Underwater Explosive | 1957 | Government Laboratories | [illegible] | XD |

SUMMARY OF RXD EVENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 4096 | Conception of the 84-Minute Pendulum to Prevent Vehicle Horizontal Accelerations from Causing Spurious Precession of a Gyrocompass | 1923 | Foreign Laboratory, Industrial | -- | XD |
| 4097 | Development of an Improved Marine Stable Element (MAST) Utilizing Post-World War II Inertial Component and System Ideas | 1954 | Government Laboratory, University Operated | 1,000 | AD |
| 4098 | Development of a Ship's Inertial Navigation System (SINS) | 1955 | Government Laboratory, University Operated | 700 | AD |
| 4099 | Development and Flight Test of the First All-Inertial Aircraft Navigation System, SPIRE (Space Inertial Reference Equipment) | 1953 | Government Laboratory, University Operated | 4,000 | AD |
| 4101 | Development of Planar Transistor Process Technology | 19[illegible] | Profit Laboratory, Industrial | 10 | XD |
| 4103 | Development of the Cytac Long-Range, Precise, Hyperbolic Radio Navigation System | 1954 | Profit Laboratory, Industrial | 500 | AD |
| 4106 | Research on a Solid-State Amplifier (Transistor) | 1948 | Profit Laboratory, Industrial | 1,000 | R |
| 4107 | Conception of Transistor with Bonded, Alloyed Contacts | 1948 | Profit Laboratory, Industrial | 3 | R |
| 4108 | Development of Method for Growing High-Purity Single Crystals of Germanium | 1950 | Profit Laboratory, Industrial | 200 | R |
| 4109 | Development of a Germanium Transistor with Alloyed Indium Junctions | 1951 | Profit Laboratory, Industrial | 50 | XD |
| 4110 | Demonstration of Zone Melting for Purification of Metals | 1951 | Profit Laboratory, Industrial | 3 | R |
| 4111 | Development of High Frequency PNIP Transistors | 1953 | Profit Laboratory, Industrial | 3 | R |
| 4112 | Development of Silicon Transistor | 1954 | Profit Laboratory, Industrial | 75 | XD |

SUMMARY OF RXD r . ENTS (continued)

| Serial Number | Title | Year (Termination) | Organization Type | Funds ($1,000) | RXD Type |
|---|---|---|---|---|---|
| 4113 | Development of an Oxide Masking Process for Delineating Diffusion Regions on Silicon Transistors | 1955 | Profit Laboratory, Industrial | 10 | XD |
| 4114 | Research on Diffusion Techniques for Transistors | 1956 | Profit Laboratory, Industrial | 300 | R |
| 4115 | Development of Thermo-Compression Bonding for Transistors | 1956 | Profit Laboratory, Industrial | 30 | R |
| 4116 | Development of Method for Levitation of a Floating Zone of Silicon | 1953 | Government Laboratory | 50 | XD |
| 4117 | Development of Molecular Electronics Amplifiers | 1961 | Profit Laboratory, Industrial | 300 | XD |
| 4118 | Conception and Demonstration of "Molecular Electronic" Integrated Circuits | 1958 | Profit Laboratory, Industrial | 500 | XD |

APPENDIX I.

DoD Funding for RDT&E and Estimated RXD Expenditures

The following table shows total DoD funding for RDT&E from 1947 through 1963. The estimated RXD expenditures are based on the assumption that about 20 to 25 percent of the RDT&E funds was spent on research in science and technology.

| Year | Total RDT&E Funding ($ millions) | Estimated RXD Expenditures ($ millions) |
|---|---|---|
| 1947 | 515 | 118 |
| 1948 | 534 | 123 |
| 1949 | 608 | 140 |
| 1950 | 539 | 124 |
| 1951 | 758 | 174 |
| 1952 | 1,164 | 268 |
| 1953 | 2,150 | 495 |
| 1954 | 2,187 | 505 |
| 1955 | 2,261 | 520 |
| 1956 | 2,101 | 485 |
| 1957 | 2,406 | 555 |
| 1958 | 2,504 | 575 |
| 1959 | 2,860 | 660 |
| 1960 | 4,710 | 1,080 |
| 1961 | 6,131 | 1,410 |
| 1962 | 7,643 | 1,308 |
| 1963 | 7,638 | 1,445 |
| | 46,709 | 9,995 |